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Decontamination Techniques for Mobile Response Equipment Used at Waste Sites (State-of-the-Art Survey)

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DECONTAMINATION TECHNIQUES FOR MOBILE RESPONSE EQUIPMENT USED AT WASTE SITES (STATE-OF-THE-ART SURVEY)

by

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A state-of-the-art review of facility and equipment decontamination, contamination assessment, and contamination avoidance has been conducted. This review, based on an intensive literature search and a survey of various equipment manufacturers, provides preliminary background material on the subject. The information developed here constitutes an important "head start" for those who need to establish preventive measures, decontamination plans, and procedures for response personnel and cleanup equipment used at hazardous waste sites.

The study discusses various decontamination methods, such as use of solvents to wash off contaminants, use of chemical means to degrade contaminants, and use of physical means to remove contaminants. Chemical and physical testing methods designed to assess the nature of the contaminant and the quantity and extent of contamination were also investigated. Also discussed in this report are procedures that can be used to prevent contamination of response equipment and personnel. These preventive procedures are: enclosures to prevent spread of contaminants, safety features on response equipment to prevent spills and leaks, protective coatings on response equipment surfaces, and protective clothing and furnishings for personnel. Three case studies were also reviewed: the Three Mile Island cleanup, the "Vulcanus" incinerator ship cleanup (dioxins and PCBs), and PCB cleanups in Binghamton, New York. The review has identified several methods that could be of value in effectively decontaminating response equipment units such as a mobile incinerator at a reasonable cost.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory helps provide an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Environmental Protection Agency; the granting of permits and other responsibilities of State and local governments; and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes decontamination and contamination avoidance techniques applicable to mobile response cleanup devices which are used at hazardous waste sites. The information presented in this report is useful for those who need to establish procedures for protection and cleanup of the waste sites' response personnel and equipment.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

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A state-of-the-art review of facility and equipment decontamination, contamination assessment, and contamination avoidance has been conducted. This review, based on an intensive literature search and a survey of various equipment manufacturers, provides preliminary background material on the subject. The information developed here constitutes an important "head start" for those who need to establish preventive measures, decontamination plans, and procedures for response personnel and cleanup equipment used at hazardous waste sites.

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CONTENTS

	PAGE
Foreword	iii
Abstract	iv
Tables	vi
Figures	vi
Acknowledgements	vii
1. Introduction	1
2. Conclusions and Recommendations	5
3. Contamination Avoidance	6
Enclosed Structures and Secondary Containment	6
Equipment Safety Features	9
Protective Coatings	11
Personnel Protective Clothing and Equipment	13
4. Assessing Contamination Levels	20
Chemical and Physical Tests	20
5. Decontamination Methods for Mobile Response Equipment	28
Solubilization Methods (use of solvents)	28
Chemical Degradation of Surface Contaminants	37
Physical Decontamination Techniques	44
Abrasive Cleaning Methods	44
Non-Abrasive Physical Cleaning Methods	49
6. Case Studies: Decontamination of Surfaces	56
Decontamination of the Binghamton State Office Building	56
M/T Vulcanus Decontamination	58
Three Mile Island Decontamination	59
Case Studies Conclusions	60
References	62
Appendix	
A. Factors for Unit Conversion	66

TABLES

NUMBER		PAGE
1	Summary of the Use of Protective Coatings for Prevention of Surface Contamination	11
2	Gunk Decontamination Preparations	30
3	Summary of Solubilization Methods for Removal of Surface Contaminants	38
4	Summary of Chemical Degradation Methods for Removal of Surface Contamination	40
5	Summary of Abrasive Methods for Removal of Surface Contaminants	45
6	Summary of Non-Abrasive Physical Cleaning Methods for Removal of Surface Contamination	52
7	Vacuum Vendors	54

FIGURES

NUMBER		PAGE
1	Mobile Incinerator Components	25

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SECTION 1

INTRODUCTION

GENERAL OVERVIEW

The purpose of this document is to provide Environmental Protection Agency (EPA) and other waste site response personnel with background information on contamination avoidance and decontamination methods applicable to mobile response hazardous material cleanup devices used at waste sites. The document emphasizes preventing contamination of the response personnel and the mobile response equipment, taking into consideration public health and safety, cost, and efficiency.

This document which is based on an intensive literature search and survey of various equipment manufacturers, represents preliminary background information on the subject. This information constitutes an important "head start" for those who need to establish preventive measures, decontamination plans, and procedures for response personnel and cleanup equipment at hazardous waste sites. This information has already been used in the field by the Releases Control Branch of the EPA Hazardous Waste Engineering Research Laboratory (HWERL), and by EPA contractors of the Laboratory.

The Releases Control Branch has developed a wide variety of prototypical hazardous material cleanup devices. This specialized, full-scale mobile equipment is capable of performing many useful and complex, hazardous chemical cleanup and treatment processes at spill sites and Superfund hazardous waste sites. These mobile response devices are deployed by EPA's Environmental Emergency Response Unit (EERU) contractor at spill and waste sites, where the equipment undergoes field demonstrations and shakedown tests.

One example of an EPA-developed mobile response unit is the Mobile Incineration System ("Mobile Incinerator") which underwent test burns of dioxin-contaminated soils. The unique feature of the EPA developed incinerator is its mobility, which facilitates its transport to waste sites.

The use of the mobile response devices at spill and waste sites inevitably leads to contamination of the devices, and their operators, with hazardous chemicals being treated. Subsequent relocation of the mobile devices may spread the contamination to the surrounding community unless controls, including contamination avoidance and decontamination procedures, are used.

Fields Contributing to the State-of-the-Art on Cleaning Contaminated Surfaces

Surface decontamination methods generally rely on techniques which are applicable to treating an assortment of hazardous substances. There are many areas which demand surface decontamination. They include:

- o Nuclear waste activities
- o Chemical/biological warfare agent cleanup
- o Chemical process equipment cleaning
- o Drum recycling.

Many methods that are presently used in these areas could very likely be extended to the decontamination of mobile response equipment.

The following sections discuss the importance of decontamination concepts relative to different fields of application. The decontamination procedures are described here in general terms. They will be addressed in greater detail in Sections 4 and 5, below.

Nuclear Waste Activities

The discharge of radioactive substances to the environment is the central hazard associated with nuclear reactors. Such discharge can occur while the reactor is in operation or when it is shut down. Maintenance of the reactor often demands removing corrosion scale from inside pipes and tanks, and these products can be radioactive. When a surface that requires decontamination has an oxidized (rust) or corroded coating, it becomes irregular, having much more total adsorptive surface area than a non-oxidized, uncorroded surface, and can therefore hold more contamination. Removing the oxide or corrosion therefore facilitates contamination removal. Decontamination reduces radiation levels to ensure personnel safety. It also keeps reactor operation at efficient levels.

Chemicals seem to be the primary agents for cleaning nuclear equipment. Various methods and formulations exist and have been tested. Selection of the appropriate method depends on the type of problem to be solved. The following list may offer general guidance (1):

- o Reduce radiation levels
- o Dissolve the oxide film
- o Prevent reprecipitation and redeposition of products

- Have minimal corrosion effects
- Provide treatment with a single application.

Chemical/Biological Warfare Agent Cleanup

The U.S. Army has conducted a number of studies on the problems associated with military personnel and equipment contamination by chemical and biological warfare agents. A chemical agent's effect depends on the type and amount with which the individual comes into contact, and the person's physical condition. Biological agents are living organisms that cause disease to the exposed individual. Again, effects depend on the agent and the individual's susceptibility. For either situation, avoiding exposure by using protective clothing and a gas mask is a prime consideration. Decontaminating an individual and his clothing (or outer protective garments) following a chemical/biological exposure temporarily removes the individual from danger.

Exposure to contamination that covers equipment surfaces, which occurs when using mobile response equipment at hazardous waste sites, remains a problem. Decontamination procedures may include rinsing the surfaces with water, detergent, or solvent, or removing the agents by physical methods such as high pressure water. In the case of biological agents, chemical methods are needed to destroy the disease-bearing organisms. Chemical methods are also used to detoxify chemical agents; they are particularly effective in penetrating the oily residues in which most agents survive.

Chemical Process Equipment Cleaning

The efficient operation of a chemical production process often depends on maintaining the purity of the streams as they pass through reaction vessels, separation units, assorted pipes, valves, and pumps. Corrosion products, dirt and oxide layers, and even vapors condensed upon inner surfaces of equipment may interfere with product quality, reaction performance, or the achievement of adequate rates of chemical transport from one process unit to the next. Likewise, auxiliary equipment such as cooling towers or heat exchangers operates best when corrosion and fouling are minimal.

Removal of internal buildup is only one reason for decontamination. Often an industry produces two or more products using the same process equipment. The equipment must be emptied and cleaned of all compounds (e.g., raw materials, intermediates, products) associated with the initial process so that foreign chemicals do not contaminate the subsequent process.

Chemical process equipment may also have to be cleaned prior to maintenance or removal from service. Cleaning the equipment before transport reduces the spread of contaminated material. Methods for decontamination are numerous. Chemical methods can circulate cleaning fluids throughout the system. Removable portions can be cleaned in immersion tanks or by physical methods. The interiors of large vessels often can be cleaned by physical methods such as high-pressure water or abrasive cleaning.

Drum Recycling

Storing chemicals in drums or other containers is a common practice. Sorting and transporting filled drums may affect personnel safety; however, empty drums also present a number of problems. Empty drums are often recycled, and total removal of chemicals from drums is difficult.

Using a drum to store a chemical that it previously contained isn't a problem, but there are hazards if a drum is to be filled with a different chemical. Decontamination must be carried out to assure that no traces of chemicals from prior uses remain. Drums may be immersed in or flushed with water or appropriate solvents. Physical methods of cleaning, such as abrasive blasting, are also common.

Case Studies

The following three case studies are discussed in Section 6 (page 56) of the report: (1) cleanup of the Binghamton State Office Building in Binghamton, NY; (2) "Vulcanus" incinerator ship cleanup (dioxins and PCBs); and (3) the Three Mile Island cleanup. As a consequence of reviewing these case studies, several methods and techniques that have applicability to decontaminating mobile response units at hazardous waste sites have been identified.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

FINDINGS

The decontamination and contamination avoidance methods discussed in this report, including physical and chemical cleaning methods, protective coatings, personnel protective clothing and equipment, and containment structures, have a wide range of advantages. The following paragraphs outline several promising decontamination scenarios, based on combinations of the methods described in this report.

Seamless surface coatings of heat and chemically resistant, durable polymers increase the ease and effectiveness of most decontamination methods for mobile response units. Also, presence of a drainage and collection system beneath mobile units for containing rinses and other surface cleaning wastes will facilitate the decontamination process.

Decontamination can be simple. Vacuuming can effectively remove gross contamination, such as particulates, from surfaces. Final decontamination may then be accomplished using either detergents and high pressure water or wet abrasive blasting. Spent wash and rinse waters may be collected and properly stored for incineration or off-site disposal.

Vacuuming or an initial water rinse to remove gross contamination, followed by the application of a solvent or acid-based foam or gel, is another approach. After allowing time for contaminant solubilization, the formulation may be rinsed off and collected for disposal. This process may be repeated to accomplish sufficient decontamination.

Areas of mobile response units that are most heavily contaminated, such as the loading area and hopper system of the mobile incinerator, may be stripped to bare metal to ensure the highest level of decontamination. One of the most promising techniques is exposure to high intensity UV light or flash blasting, which destroys contaminants at temperature flashes of 2,760°C. In some cases, heavily contaminated areas may be disassembled and cleaned separately via high pressure FREON™ or ultrasonic cleaning.

Tables 1 through 6 summarize methods of decontamination and contamination avoidance. Applications, limitations, and capabilities of each method are also presented.

SECTION 3

CONTAMINATION AVOIDANCE

INTRODUCTION

To maximize the effectiveness of decontamination procedures, chemical manufacturing industries commonly apply methods that reduce or prevent contamination of equipment at hazardous waste sites. This section will investigate various methods which can be applied to avoid contamination of mobile response equipment during its use at waste sites. Specifically, this section provides descriptions of the following methods for avoiding contamination:

- Enclosed structures and secondary containment for the mobile response units
- Equipment safety features
- Protective coatings for the mobile response equipment
- Personnel protective clothing and equipment.

ENCLOSED STRUCTURES AND SECONDARY CONTAINMENT

Enclosing or containing operating equipment is a principal means of minimizing exposure of surrounding communities or properties to hazardous materials during operation. This can be accomplished through 1) enclosure (i.e., overhead structure) of the mobile response equipment to minimize air transport of materials, and 2) secondary containment, such as dikes, drainage systems or lined impoundments around potential points of release to minimize surface transport of materials.

Enclosures and secondary containment can be applied alone or together to cover the entire mobile response system, or only those components that are potential sources of significant release (e.g., feed system, ash collection on a mobile incinerator). Constructing an enclosed structure with some level of secondary containment would limit the contaminated area to a relatively small area, thereby reducing the efforts required for decontamination of the mobile response unit and its surroundings.

A variety of commercially available systems for enclosing large areas have found application in the waste management industry. Also, various secondary containments can be applied to the mobile response systems wherever

spills are prevalent. The following sections provide a brief summary of enclosed structures and secondary containment methods. Examples of such systems, approximate costs, and limitations of implementation are provided, where possible.

Enclosed Structures

Using a structure to house the mobile response system can significantly reduce contamination of surroundings during the unit's operation. Fugitive emissions during operation could be contained within the enclosed structure, enabling rapid cleanup before dispersion of contaminated material occurs. Careful study must be given to the potentially increased concentration of contaminants within the building structure, which could increase the potential for worker exposure. Enclosed structures are considered here as a means to limit spreading contaminants during operation through air, rainwater, and spill transport mechanisms.

The following criteria were used in evaluating enclosed structures:

- Area covered by the enclosure
- Ease of installation and maintenance
- Economics.

One type of commercially available enclosure is an air inflatable structure. This type of building may have an inside clearance ranging from 20 to 30 meters, depending on the manufacturer. These buildings can be designed to have a clear span up to 90 meters and a length of 240 meters. The building is kept inflated with a series of fans for which most manufacturers provide backup generators in case of power failure. The building can be easily anchored to a 1-meter wide, 1-meter deep continuous grade beam. These structures can be easily relocated by pouring a new foundation. The capital costs quoted by representative vendors vary from $30 per square meter (Thermo-flex) to $100 per square meter (Bird Air Inc.) Special care must be taken to separate the mobile response unit from the rest of the waste site to prevent the accumulation of hazardous levels of combustion byproducts from building up inside the structure. The mobile response unit, especially the mobile incinerator, must be kept in a well ventilated area to prevent the accumulation of gases and particulates.

Arch structures are another type of commercially available enclosure which provides greater structural support than typical air-supported structures. Arch structures are made of steel with 50-meter spans (Wonder Buildings). The lengths of these buildings are virtually unlimited, and heights vary from 6 to 18 meters. These buildings are easily relocatable and have minimal operating and maintenance costs. Capital costs for this type of structure range from $100 to $200 per square meter.

Conventional prefabricated-type construction could also be applied. A "Butler" pre-engineered steel building has a span of 36 meters with a 7-meter high cave, and is 90 meters long. Although it is perhaps the easiest building to construct and one of the most permanent, its relocation is rather difficult. Costs vary from $80 to $100 per m^2. The building would have to be demolished and removed after the job is completed, and treated as hazardous. The "Butler" type building also prevents negative pressure, which is a condition that can occur in an air supported or totally enclosed building when, as in the case of the mobile incinerator, primary and secondary combustion create heavy demands for air. High negative pressure should be avoided since it would tend to starve an incinerator of oxygen thus causing incomplete combustion. Low negative pressure can be beneficial however, since this would cause fugitive emissions to be contained.

Fabric supported by an arch system could also be applied. Polymer fabrics such as a polyester material manufactured by Thermoflex are commonly available for this use. These buildings need relatively small foundations and are easy to relocate. The initial costs range from $200 to $400 per m^2.

The enclosed structures will become hot inside and may be very uncomfortable for the workers; therefore, some type of ventilation system should be installed to assure tolerable working conditions. Although it costs from $100 to $200 per m^2, an arch structure would provide a comfortable enclosure. It is easy to install and has minimal operating and maintenance costs.

Secondary Containment Methods

Secondary containment is a commonly applied spill control measure employed by industrial and manufacturing facilities. Secondary containment systems are typically lined areas (concrete, metal, clay, polymer lining materials) that provide a catchment for inadvertently spilled or leaked materials, minimizing their escape across the surface or through the soil. They provide temporary containment, allowing spilled materials to be cleaned up before they contaminate surrounding environments.

Secondary containment applied to the mobile response unit during operation can protect against hazardous material leakage to surroundings. Containment can be applied areawide (i.e., around the entire unit) or at points in the unit where leaks or spills are most prevalent (e.g., feed system, ash collection system in a mobile incinerator).

A simple, effective secondary containment measure is a 20 centimeters sloped combed concrete slab. The slab can be coated by an impermeable polymeric material, such as polyvinyl chloride (an epoxy resin), to minimize hazardous material permeating the concrete. The slab can be sloped into a collection sump to ease collection of spilled materials and wash water off the pad. Any spilled material would collect in the sump and be pumped using bulk tank vacuum pumps. The cost of a concrete pad for the incinerator unit is estimated to be $8,200 for a pad with dimensions of 50 m x 5 m x .22 m.

Containment method with the "Butler" type building would possibly be the best alternative for construction on waste sites, due to low costs and ease of construction.

Another effective technique would use a polymeric fabric cover. The cover could be placed over the immediate area in which the mobile response system is operating. The cover, made of an impervious material (i.e., polyurethane or high density polyethylene), could be placed over a compacted fill area. To avoid any tears in the fabric, plywood planks should be laid as tracks for the wheels. The fabric cover could then be collected and incinerated. Although not as structurally sound as a concrete containment system, this system is easy to install, remove, and clean up.

Consideration should be given to selecting the secondary containment scheme. For most applications, a concrete pad would provide good structural support for the mobile response unit; it would be easy to clean if coated, and it would be relatively inexpensive.

EQUIPMENT SAFETY FEATURES

An effective way to avoid contamination of the mobile response unit exterior and reduce decontamination efforts is to consider design options which incorporate safety or leak minimization features. This section will review the engineering design of the mobile response equipment and point out possible causes of failure based on industry experience. A study conducted by the National Institute of Occupational Safety and Health (NIOSH) April, 1981, has concluded that in petroleum refineries and other chemical processing industries, a major source of worker exposure to hazardous chemical compounds are fugitive emissions (gaseous and liquid) from seal and fitting components of the chemical processing equipment employed.

The reality of the imperfect and variable performance of chemical process equipment seals and fittings makes preventing fugitive emissions difficult. To reduce fugitive emissions, equipment components using seals and fittings should be examined to:

- Identify potential sources of emission within the equipment
- Recommend changes in the equipment to reduce emissions.

A discussion of process equipment employing seals or fittings follows.

Pumps

Industry uses a variety of pumps, including centrifugal, positive displacement, reciprocating, piston, rotary, diaphragm, and screw pumps. The source of emission from most pumps is the drive shaft seal (2). The function of the drive shaft seal is to prevent fluid from escaping through the clearance between a rotating shaft and the wall or a housing or pressurized vessel.

Common causes of failure in mechanical seals include: incorrect seal assembly, improper materials or seal design, fluid contamination, poor equipment conditions, and worn-out seals. The leakage rates are normally small; nonhazardous or nontoxic fluids may quickly evaporate or dissipate into the atmosphere. However, pumps for hazardous and toxic fluids require other means to contain contaminants (3).

To contain hazardous materials, most pump manufacturers serving the Chemical Process Industry offer double or tandem seals to control fugitive emissions. The bellows-type seal is common in many applications; it is considered safer and less prone to trouble and leaks than other types of seals (4). Another containment procedure uses magnetic drive pumps without seals. These pumps have no shaft that could wear, leak, need replacement, or reduce power. A magnetic coupling acts as a clutch to eliminate overload and motor burnouts. Magnetically driven pumps are available in a variety of capacities. Ratings range from 30 gpm pumps to giant-drive pumps that are rated at 5,000 lb/in^2, and operate in temperatures of -200° to 260°C. Jacketed design of custom centrifugal, axial flow, and canned rotor high-pressure or high temperature pumps are other possibilities for fugitive emission control. Hermetically sealed, these zero-leakage pumps offer the advantages of operating temperatures from cryogenic to 540°C, pumping rates from 30 to 1,200 gpm, and standard design to handle 340 atm.

Seal-less slurry and acid pumps that have no packing, water glands, or mechanical seals continue to find special service applications in the Chemical Process Industry. These pumps do not leak while running because a secondary set of pumping vanes (expellers) creates a hydraulic seal. The expeller keeps liquid out of the shaft as the impeller pumps material through the discharge. As the pump shuts down, powerful springs close the two seals. A drip pan may be used for additional safety (4).

Valves

Valves serve not only to regulate fluid flow, but also to isolate piping or equipment for maintenance without interrupting other connected units. Various valves used in industry are: gate, globe, angle, butterfly, ball, and diaphram valves. The emission sources associated with most valves differ, depending on whether the valve is placed in-line or is open-ended. If the valve is in-line, emission sources are the stem and bonnet of the valve. If the valve is open-ended, emission sources are the stem, bonnet, and flow seal (2).

Industry has opted to use packless-type valves to reduce fugitive emissions. Two options are investigated. 1) Bellows sealed valves use a bellows for leak-tight service. The bellows are manufactured from ductile metal tubing. By sealing one end of the bellows to the valve stem and the other end to the valve body an all metal seal is achieved while maintaining vertical movement of the valve stem. These packless bellow-seals permit zero leakage past the stem. 2) Diaphragm valves are excellent for fluids containing suspended solids. The fabric reinforced diaphragms may be made from natural rubber, synthetic rubber, or natural or synthetic rubber faced with Teflon®. Diaphram valves are, however, limited to pressures of approximately 3.4 atm. (5).

Piping Systems

Piping systems are another area where fugitive emissions may occur during process operations. Piping systems incorporate flanges, elbows and tees, straight piping sections and various other types of fittings. Because fugitive emissions occur at these fittings, designing piping systems requires careful consideration. For example, a slurry transport pipeline should be designed to minimize sharp elbows and turbulent flow patterns (2); as this increases the severity of corrosion.

Other considerations when specifying a piping layout would be to use high temperature, high pressure seals at pipe joints. And using other pipe materials such as stainless steel or Inconel, since these materials resist corrosion well. Incorporating a pipe monitoring plan, using X-ray or special metallographic examinations should also be considered when installing a piping system. Installing drip pans around pipe joints and valves is an effective method of monitoring for leaks or faults in the piping system. In essence, incorporating equipment safety features in the mobile response apparatus effectively avoids contamination.

PROTECTIVE COATINGS

The chemical industry typically applies paint to protect surfaces against corrosive chemicals. Use of paint minimizes contaminating metal surfaces and provides a surface that can be easily removed or cleaned to eliminate settled contaminants. These coatings must be selected according to how easily they are applied, decontaminated or cleaned (See Table 1).

TABLE 1. SUMMARY OF THE USE OF PROTECTIVE COATINGS FOR PREVENTION OF SURFACE CONTAMINATION

	PERMANENT COATINGS	TEMPORARY COATINGS
REMOVAL OF BASE METAL	Negligible	Negligible
AREA OF APPLICATION	External	External
QUANTITY OF WASTE PRODUCED	Moderate	Moderate-Large
WORKER EXPOSURE	Low	Low-Moderate
OVERALL COSTS	Moderate	Moderate-High
COMMENTS	Easily applied with a brush, spray system, or roller.	2 or more coats needed, allow over 24 hours to cure.

Surface contamination can originate from a number of sources: (1) Absorption of impurities (e.g., hydrocarbons) from the ambient air, (2) Reaction of the surface with the reactive species (e.g., oxygen, sulfur), and (3) Preferential diffusion of one component (in case of multi-component materials), which can cause variable composition-type surface contamination. The contaminants caused by these sources are film or layer-type in nature (6).

Generally, decontamination by either chemical or physical means effectively removes materials such as soils, chemical compounds, metal fines, and reaction products from a surface. Surface contaminants can be removed chemically by strong reagents (acids, alkalis) that simultaneously prevent their redeposition. Physical methods range from abrasion to ultrasonic cleaning. (See Section 5 for a discussion of cleaning methods).

Experience has shown that surfaces (metal, concrete, etc.) overlaid with a protective coating are easier to decontaminate (7). These coatings can be either permanent or temporary. Available coatings are discussed below.

Permanent Protective Coatings

Permanent protective coatings are polymeric materials that can be applied to metal and other surfaces for long-term use. They are intended to provide an easily decontaminated surface that protects migration into structural materials. These coatings could remain on the equipment for many years without removal. The criteria used in the selection of a suitable permanent coating are:

- Resistance and compatibility to environmental dusts and vapors
- Ability to withstand chemical and physical decontamination procedures
- Ease of application
- Adherence (adhesiveness) to the metal surface.

Based on these criteria, the following coating materials are candidates for permanent coatings:

- Epoxy Resins
- Phenolic Resin Coatings
- Chlorosulfonated Polyethylene

Temporary Coatings

An envelope of a polymeric material that can be peeled off or removed in some other way can often meet the requirements for temporary protective coatings. These coatings protect the enclosed metal from corrosion and mechanical abuse. Because they can be peeled off and subsequently incinerated, temporary coatings do not require the physical and chemical decontamination methods that permanent coatings do. The following can be used as temporary/strippable protective coatings:

- Chloride acetate copolymers are most suitable for strippable surface coatings. An effective coating used in many applications is composed of a plastic spray in solution of copolymers. This coating can withstand a variety of chemical environments, and after use, it can be easily stripped and incinerated (10).

- In certain instances, layered coatings, one layer of which can be selectively dissolved and removed from another without ruining the base coating, may be needed to facilitate decontamination. An epoxy overlaid with polyvinyl chloride (PVC) is such a combination. Other combinations include PVC over modified phenolic, epoxy polyamide cured, and inorganic zinc (7).

- Plastics employed as strippable coatings are largely vinyls, cellulose acetate, ethyl cellulose, or cellulose acetobutyrate. They have been used in a variety of industries and can easily be stripped and incinerated (11).

- Polyurethane is also a good temporary protective coating. It shows high chemical resistance and is durable. Polyurethane coating can be sprayed or brushed on and is easy to remove.

- For small areas, protective tapes can prevent contamination. Tapes made of polyvinyl chloride, polyethylene, and fluorocarbons are used in various industrial operations. These tapes can easily be stripped and incinerated.

A variety of permanent and temporary protective coatings have been investigated in this section. Although there are other coatings available, they are less effective and more expensive. Based on the coatings investigated, layered coatings using an epoxy overlaid by PVC seem to be a promising technique to protect mobile response equipment.

PERSONNEL PROTECTIVE CLOTHING AND EQUIPMENT

The temporary nature of hazardous waste site work eliminates sophisticated engineering controls (such as piped ventilation systems) as feasible methods for preventing or controlling worker exposure to toxic materials.

Instead, safe work procedures and personnel protective clothing and equipment must be used. How successfully work procedures and protective clothing guard worker health depends on worker cooperation. Carefully prepared standard operating procedures (SOPs), effective employee training, and supervisory enforcement of the safety and health plan are necessary to maximally protect each worker from toxic exposure.

Various safety equipment will be required during the field work associated with mobile equipment operation and decontamination of mobile equipment. Because of the variety of the tasks to be performed and their associated exposure levels, it would be prudent to determine a standard for the level of protection necessary for each phase of operation. The following sections discuss:

- Guidelines for determining levels of protection necessary for various potential exposure situations
- Selection and use of personal protective equipment in accordance with the guidelines
- Temporary emergency response
- Mobile decontamination units.

Levels of Protection

The Office of Emergency and Remedial Response of the U.S. Environmental Protection Agency has prepared final standard operating safety procedures for hazardous waste spill site control and entry. The following discussion and the system for selecting protective equipment based on four levels of protection are adapted from the SOP of EPA's Emergency and Remedial Response Division, 1985 (8).

Insufficient knowledge of toxicity levels at a particular site precludes advance selection of any but the highest level of personnel protective equipment. Initial estimates of the toxic and hazardous wastes (including carcinogens) at a site must be empirically determined to ensure worker safety. This may be modified after adequate data is collected on the actual levels of toxicity.

Level A Protection

Level A protection should be worn when the highest level of respiratory, skin, and eye contact protection is required; exposure to toxic materials can cause illness. Situations warranting this level of protection should be remedied by removing the inherent hazard through mechanical means, engineering design, or structural enclosures.

However, should this high level of protection be imperative, the personnel protective equipment required for Level A protection includes:

- Positive pressure self-contained breathing apparatus (SCBA) operated in the positive pressure mode
- Totally encapsulating chemical resistant suit
- Gloves--inner (tight-fitting and chemical-resistant)
- Gloves--outer, chemical-resistant
- Boots--chemical resistant, steel toe and shank
- Hard hat--optional.

Level B Protection

Level B protection should be selected when either the highest level of respiratory protection is needed but exposure to the small unprotected areas of the body (i.e., neck and back of head) is unlikely, or toxicity concentrations are within acceptable exposure standards. This level of protection is essential if worker illness through exposure is likely. Similar to the Level A protection, Level B protection is appropriate only in extreme cases when other alternatives are not feasible.

Personnel protective equipment required for Level B protection includes:

- Positive pressure SCBA operated in the positive pressure mode
- Hooded, two-piece, chemical-resistant-type coverall suit
- Gloves (inner and outer)--chemical resistant
- Boots--chemical resistant, steel toe and shank
- Hard hat--optional.

Level C Protection

Level C protection should be selected when: (1) the type(s) and concentration(s) of respirable material are known, (2) the material has adequate warning properties or is assumed to be less than the protection factors associated with air-purifying respirators, and (3) exposure to the few unprotected areas of the body (i.e., neck and back of head) is unlikely to cause harm.

Personnel protective equipment required for Level C protection includes:

- Full-face, air-purifying cannister or cartridge respirator (full-face respirator can be worn instead of non-vented goggles if eye irritants are present)
- Safety goggles (non-vented if not full face respirator)
- Chemical-resistant clothing
- Hooded, two-piece, chemical-resistant Tyvek coveralls
- Gloves (inner and outer)--chemical resistant
- Escape mask
- Hard hat--optional
- Boots--chemical resistant, steel toe and shank.

Level D Protection

Level D is the basic work uniform and should be worn for all site operations not requiring greater protection. Level D is appropriate only when sites are positively identified as having minimal toxic hazards.

Personnel protective equipment required for Level D protection includes:

- Chemical-resistant Tyvek coveralls
- Boots/shoes--safety or chemical-resistant, steel-toed boots
- Escape mask
- Safety glasses or safety goggles
- Hard hat (face shield optional)
- Half-face cannister or cartridge respirator (carried)
- Gloves (carried).

The Selection and Use of Personnel Protective Equipment

The Site Health and Safety Officer (SHSO) should determine the level of protection necessary for each operation, based on a discussion of conditions with the Project Leader. Through periodic inspections, the SHSO will ascertain that the users of the equipment are maintaining its effectiveness through regular care, cleaning, and repair according to the manufacturer's instructions.

Boots must be worn at all times at all sites. The boots should be leak proof, chemically resistant, and steel-toed. These boots preferably should be the type which directly covers the foot (with socks), rather than another boot.

The gloves must be leak proof and chemically resistant. The glove material should be chosen based on the waste constituents expected at the site. In the absence of such information, the gloves should be neoprene or nitrile rubber. Nothing at the site should be touched without gloves. For warmth, cotton gloves may be worn underneath. Clean surgical gloves should be worn under the neoprene gloves. A two-glove system is standard practice, with the second glove serving to remove other articles of clothing during the decontamination process (EPA Peer Review, 1985).

Some type of eye protection shall be available for all operations. Non-vented goggles should be worn in the presence of irritating vapors. These goggles should be chemical and splash-resistant. Half-face respirators should be worn with goggles for eye protection. The goggles must fit snugly and not interfere with the respirator seal. When not in use, the goggles may be worn on the safety helmet. When irritants are not present and a full-face respirator is not required, safety glasses or vented goggles may be worn to protect eyes from flying objects or liquid splashes.

The coveralls should be splash repellent and chemically resistant. Disposable Tyvek coveralls are successful for this purpose and cost around $4-$5 each. Other suits such as PVC or vinyl (raingear) can also be worn in Level "B" or Level "C" protection. Fully encapsulating reusable suits (usually butyl rubber) should be worn in confined areas that may contain toxic substances (e.g., the temporary enclosed structure of mobile response equipment), and in areas where toxic substances that are absorbed through the skin are present. The costs of fully encapsulated reusable suits made of Chloropel™ range from $5,351 per suit (Lab Safety Supply), to $670 per suit (Preiser/Mineco).

Three types of respiratory protection must be available to the site workers: half-face cannister or cartridge respirators, full-face cannister or cartridge respirators, and self-contained breathing apparatus (SCBA). The SHSO should inspect all SCBAs and other protective gear weekly, whether used or not, and should keep a written record of the inspections.

Disposable protective equipment is well-suited for many decontamination procedures since extensive cleaning or reconditioning of the equipment after use is unnecessary. Disposable gear especially useful in decontamination operations include: Tyvek coveralls, various hat and shoe covers, shoulder-length plastic gloves, durable plastic gloves of all types, lightweight plastic jackets and trousers, boots of all types, and air purifying cartridge and filter respirators.

An effective procedure for cleaning reusable protective clothing is to: (1) place the protective gear in a rinse tank containing a solution of warm water and a compatible soap or detergent (Alconox), (2) scrub the gear with

a brush, and (3) thoroughly rinse the clothing with clean water. For respirators, NIOSH recommends that the mask parts (with filters removed) be placed in a 5 percent solution of sodium hydroxide or a strong alkaline solution for 1 or 2 minutes, followed by a thorough rinse with clean water. Cleaning mask parts with a cleaner-sanitizer, such as a dilute solution of ethanol, is also possible (2). Another commonly used cleaning method in the field is an alkaline wash (sodium carbonate and detergent or Borax and detergent) followed by a fresh water rinse (using a quaternary ammonium chloride instead of alcohol) and air drying (EPA Peer Review, 1985).

Other cleaning techniques employed are: (1) using a commercial dishwasher for cleaning respirators, and (2) using a standard domestic-type clothes washer with a rack installed around the agitator to hold the face pieces in fixed positions. In both cases any good detergent may be used, but cleaner-sanitizer solutions are more effective.

Mobile Decontamination Units

Personnel protective equipment is very important in controlling worker exposure to the toxic environment. However, protective clothing can accumulate contaminants on the surface. Therefore, the worker needs to go through a decontamination process before leaving the site. This prevents workers from carrying residual chemicals home and thereby exposing their families. Methods have been established to eliminate this hazard. Maximum and minimum standards have been set which should be strictly enforced. The minimum requirement for Levels A, B, and C require stations to be set up to perform each task listed below:

1. Place all equipment used on-site (tools, sampling devices and containers, monitoring instruments, radios, clipboards, etc.) on a plastic dropcloth. Keeping equipment separated at the site will prevent cross contamination.

2. Scrub outer boots, outer gloves, and suit with decontamination solution or detergent and water. Rinse well with water.

3. Remove outer boots and gloves. Drop in plastic-lined container.

4. Exchange workers' air tank or canister (mask), put on new outer gloves and boot covers, tape all joints.

5. Remove boots, suit, and inner gloves and deposit them in separate plastic-lined containers.

6. Remove breathing equipment. Avoid touching face with hand. Deposit in plastic-lined containers.

7. Wash hands and face thoroughly. Shower as soon as possible.

Another effective decontamination process is the use of mobile decontamination units. The worker enters the decontamination unit, passes through the contaminated change area, and gets out of the protective equipment. Next, the worker proceeds to the showers, which can be somewhat effective in removing particulates left on the body. After showering, the worker enters a clean room and dons his street clothes.

Evergreen Industry provides mobile decontamination units. Each unit is made of aluminum and is fully insulated; it features a negative-pressure blower system with a high-efficiency filter for clean emissions. It also features a holding device for wastewaters generated by cleaning of equipment and personnel.

SECTION 4

ASSESSING CONTAMINATION LEVELS

INTRODUCTION

Decontamination of surface-contaminated substances involves the chemical/physical removal or destruction of harmful substances from solid surfaces (soil, metal, wood, glass, etc.) or from the air. After the contaminated area and associated components are identified, a series of chemical/physical tests are performed to quantitatively measure the levels of contaminants present in the subject area. Before initiating decontamination operations, a detailed work plan specifying the procedures, analytical techniques, and safety criteria to be employed should be prepared. The final step is to implement the procedures and analyses as specified in the decontamination plan.

CHEMICAL AND PHYSICAL TESTS

The chemical/physical test(s) initially performed to detect the presence of hazardous contaminants should consider:

- Determination of an acceptable level of decontamination
- Specific sensitivity -- the degree of sensitivity/accuracy attainable by the test and its ability to meet the required detection limits.
- Ease of application -- the ability of in-house personnel to perform the test.
- Level of analysis -- whether the sample test results can be analyzed on-site using a mobile laboratory and in a reasonable amount of time.
- Portability of equipment -- whether the test equipment is capable of being used in the field. Whether the test equipment requires any special services (electricity, plumbing, ventilation, etc.)
- Samples handling -- the requirements for sample preservation and transportation.

Chemical and physical tests for contaminant analysis are categorized into surface tests and instrumental tests. Both categories are described in more detail in the following sections.

Surface Tests

Tests that verify whether surfaces are contaminatd with specific substances are an important component of the decontamination procedures. These tests utilize chemical solvents, water, and ultraviolet light as sampling media. The surface tests are typically performed manually or by the use of visualization reagents.

One form of surface test utilizes a substrate which is impregnated with an appropriate solvent (ethanol, benzene, water, etc.). First, the impregnated substrate is wiped onto the test surface to absorb the contaminant material; next, the substrate is extracted and tested by an appropriate analytical method. Although these tests are referred to by various names, such as wipe test, swipe test, smear test, leach test, and so on they are all minor variations on a basic test procedure.

Variations for these surface tests include:

- Wiping a predetermined amount of surface area with a solvent laden swab, gauze, or filter paper. The sample is then solvent extracted prior to analysis. Wiping tests are best used with smooth, nonporous surfaces such as metal, painted wood, plastic, or glass.

- Samples can be leached from surfaces by placing a filter paper, or other suitable extraction medium on the surface to be sampled and wetting the filter paper with a solvent. The filter paper is left on the surface until dry, then removed and analyzed in an appropriate manner. This method works well with rough or porous surfaces which cannot be wiped (12).

Another method of surface testing depends on direct visualization of a reaction in the form of a color change or precipitate formation. With these tests the type of contamination must be known to choose the correct visualization reagent. Weeks, et.al. (12) described this method of detection for some cancer suspect primary amines on metal, painted, and concrete surfaces. The chromogenic spot tests set forth by the authors are sensitive and simple. To perform these tests, a visualization reagent that will indicate the presence of the contaminant is applied by brush, pipet, or spray bottle to a portion of the surface and allowed to dry. Once the surface dries the indicator color or precipitate appears on the sampling area if contamination is present. Limits for detecting the amine contaminants with this technique were reported as follows:

Stainless Steel - 10 nanograms/cm^2
Painted Surfaces - 150 nanograms/cm^2
Concrete - 2-5 micrograms/cm^2

These tests, as performed by Weeks et al.(12), have been shown to be very sensitive; however, the significance of these results in terms of personnel hazard is not known.

Instrumental Testing

Instrumental testing relies on instruments which provide a qualitative and quantitative analysis of the type and level of surface contamination. Instrumental testing for surface contamination can be monitored by ultraviolet light and by various spectroscopic techniques such as photo-acoustic, multi-reflection-infrared, and luminescence. The major advantages of instrumental testing over surface testing are:

- Instrumental testing is non-destructive (no solvents) to the test surface.
- Instrumental testing is functional on any chemical species regardless of its physical state.

One promising tool that uses ultraviolet light analyses for detecting organic compounds is the portable fluorometric monitor (13) (14). This tool is in the developmental stage and not commercially available; however, in pilot tests performed to detect surface contamination on polyaromatic hydrocarbons (PAH's), the monitor proved to be a valuable asset. It consists of a hand-held optics unit and a battery-powered electronics console. The two pieces of equipment are attached by an umbilical cord to an electronics console and secured to an operator via a shoulder harness. In pilot tests, the unit has monitored work areas and surfaces at distances of up to three meters.

The major advantages of this unit are:

- Operates easily and reliably
- Functions in direct sunlight or indoors in the presence of strong background illumination
- Provides a quantitative measure concerning the amount of fluorescent material present
- Discriminates between fluorescence of organic materials and some inorganic compounds based on their fluorescence lifetimes
- Detects materials spilled or present on a variety of working surfaces including metals, plastics, and fabrics.

Molecular luminescence spectroscopy has been shown to be a versatile and efficient surface detection technique. Both Schuresko (13) and Vo-Dinh (14) have used this method to detect various coal and oil shale wastes. These researchers also feel that the fluorometric monitor may be a reliable technique for monitoring surface contamination by other organic pollutants.

Testing Procedures

Accurate and reliable contamination sampling can be achieved only if stringent sample gathering and analysis procedures are implemented and adhered to during sample testing. A few basic procedures must be followed:

- Secure all necessary sampling tools and containers
- Apply the necessary preservation techniques to maintain sample integrity during transport and in the laboratory
- Follow a viable analytical procedure for determining whether or not the contaminant compound exists.

Obtaining a representative sample is a key factor in assessing contamination of equipment. A well designed sampling procedure that has addressed all the factors which may bias the sample should be followed. Has the proper solvent been chosen? Is the extraction medium adequate? Can an instrumental method be used?

After a sample has been obtained, it must be handled in a manner that preserves its condition during transportation to the laboratory. Light and high temperature, two factors which will degrade many samples before they can be analyzed, should be avoided.

Prior to analysis, a working analytical procedure needs to be referenced or developed. Desirable characteristics of qualitative procedures for determining contamination of equipment surfaces are adaptability for field use, direct reading, specific sensitivity, and simplicity of operation (15). Field usable spot tests have been developed for some primary amines (16). A book of spot tests that analyzes for functional groups of organic compounds is also available (17). Most test methods found in this reference can be adapted for use in a modest field laboratory. There are, however, some chemical compounds which will require analysis by a fully outfitted laboratory.

Equipment Testing

As an illustration of analysis and testing, the Environmental Protection Agency's mobile incinerator will be considered as an example, with dioxin contaminated wastes as the incineration material. In order to identify potential areas of surface contamination the mobile incinerator can be divided into five distinct components. Selection criteria for each component were based on the relative location and level of susceptibility to dioxin contam-

ination. This methodology should be useful in identifying appropriate levels of contaminant sampling and cleaning necessary for the mobile incineration unit. These five component areas are:

1. The Solids Ram Feed System -- The ram section in kiln atmosphere is made of Inconel 671, and is a high priority due to its relatively central location. The waste liquid/sludge feed nozzle hydraulic power units and ram feed unit should be given special attention during contaminant sampling and decontamination cleanup. A series of "before and after" surface contaminant sampling procedures should be implemented to ensure that a proper level of cleanliness has been achieved. Preliminary tests will indicate the extent of decontamination required and hot spots. Repeat tests will indicate if further decontamination is necessary.

2. The Rotary Kiln and Secondary Combustion Chamber Duct -- This area ranks relatively low with regard to contaminant sampling and decontaminant cleaning. Since the kiln is a self-contained unit, the exterior surface should remain relatively free from exposure to dioxin-laden soils or particulates under normal operating conditions. The rotary kiln is fabricated from carbon steel as a shell and is lined with six inches of refractory brick. The duct leading to the secondary combustion chamber is made of Inconel 601.

3. The Secondary Combustion Chamber -- This component should receive a moderate level of contaminant sampling and security. Potential hot spots are the wetted throat Venturi quench and quench elbow sump. These areas should be kept under constant surveillance for proper operation. The secondary combustion chamber is also made of carbon steel and is lined with refractory brick. The wetted throat venturi and quench elbow are made of Inconel 625. These two parts should be tested frequently since deposition of hazardous residues is likely due to the rapid drop in temperature at this point. A series of "before and after" tests should be performed around the joints and seams to ensure a safe level of operation.

4. The Ash Handling System - This system warrants moderate contaminant concern. Potential trouble spots are the sump in the base of the continuous high-efficiency air filter and the fiberglass filter mat. These components are enclosed in stainless steel and Inconcel 625 housings, respectively.

5. The Pollution Control System - Due to its relative location, this component presents very little decontamination concern. A rigorous program of ultraviolet spot tests and air sampling should be implemented to ensure that proper levels of dioxin-laden contaminants have been destroyed by the incineration process. This system is fabricated from Inconel 625 and stainless steel.

This methodology has been established to provide a quick and easy assessment of potential trouble spots in the mobile incineration unit. The level and degree of testing for dioxin contamination should be based on predetermined safety criteria.

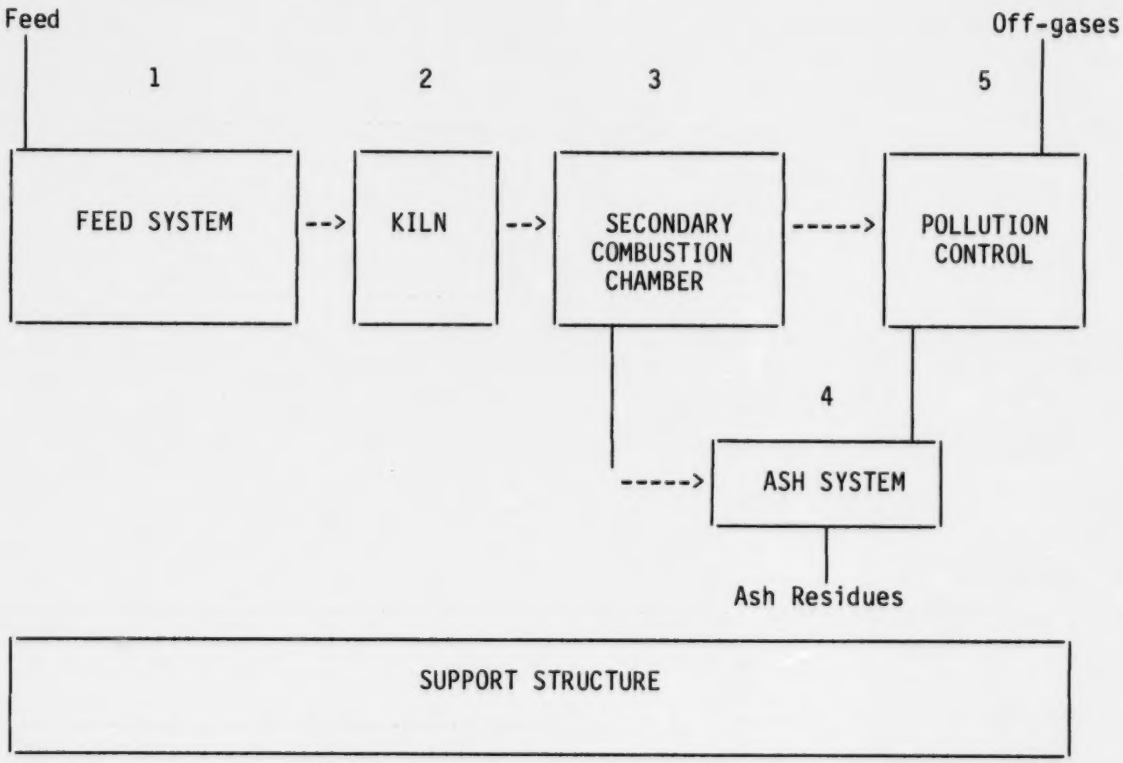

Figure 1. Mobile Incinerator Components

Analytical Procedures and Techniques

Accurate and dependable dioxin contamination testing can be achieved by implementing rigorous testing procedures and following them during testing. To date, however, methods for analyzing certain compounds have not been perfected, one of these compounds is 2,3,7,8-TCDD. The methods presently used to analyze dioxin are:

- o U.S. EPA Method 8080 to test for chlorinated dibenzo-p-dioxins.
- o U.S. EPA Method 8250 to test for the concentrations of semi-volatile organic compounds in solid wastes.
- o Modified U.S. EPA Region VII, testing protocol for 2,3,7,8-TCDD.

This last method recently has been developed under the U.S. EPA contract laboratory program, and is published in Invitation for Bid (IFB) #WA 84A002.

Each method above utilizes some form of solvent extraction followed by low/high resolution gas chromotography or low/high resolution mass spectrometry. The EPA mobile laboratory contains a gas chromatograph/mass spectrometer (GC/MS), two gas chromatographs equipped with flame ionization and infrared and fluorescent spectrometers.

Sample Analysis

Determining individual isomers of chlorinated dibenzo-p-dioxins in samples is time consuming and costly. To assure that data are valid, strict controls must be placed on all samples analyzed. W.B. Crummett et al. (18), have cited some advanced analytical techniques concerning the detection of polychlorinated dibenzo-p-dioxins in environmental samples. They point out that a good analytical system must be capable of separating or resolving each chlorinated dibenzo-p-dioxin from the 74 other possible chlorinated dioxins. The sampling methods and analytical techniques cited provide an in-depth look at the level of complexity required to test for dioxin contamination.

Crummett et al. (18), utilized solvent extraction (benzene via a Soxhlet apparatus) to remove dioxin-contaminated particulates from field samples. A benzene extract was passed through a three-column cleanup step to remove any interferences that may have been present in the sample. Then, a sample effluent was passed through a flash chromatographic column packed with alumina. The entire solution was washed with hexane to remove excess hydrocarbons and chlorobenzenes. Following dilution with a solution of 50 percent methylene chloride to remove chlorinated dioxins and dibenzofurans, the sample was fractionated. Reversed-phase, high performance, liquid chromatography on zorbax and methanol was utilized to remove all chemically similar species and to separate the chlorinated dioxins by degree of

chlorination. Gas chromatography mass spectrometry was subsequently employed to separate and measure the specific isomers present in the sample.

This scenario provides an illustration of the complexity and level of effort required to test for dioxin in the environment. In general, assessing contamination levels by sampling the contaminated surface and analyzing the sample can be a time consuming and difficult process. The objective is to develop a method for sampling and analysis that is simple to use in the field and gives direct, reliable readings. However, surface sampling and analysis raise many problems which need to be addressed.

The following questions arise: How clean is clean? Are the analytical or other detection methods able to test down to a health based standard level? If not, to what surface concentration can the analysis method be sensitive? Is an analysis method available for the type of compound being tested? Can the analysis method be used in the prevailing situation without risk of interferences? Sampling of surfaces also poses some difficult questions. Since there is little information regarding surface sampling protocols, how can one obtain a representative sample? What methods should be used to sample rough or porous materials such as concrete or unpainted wood?

Situations in which sampling and monitoring are required will most likely be unique, especially regarding sampling method, solvent extraction, visualization reagent, and analytical protocol.

Solutions to these questions are best discovered by a person who has had extensive experience in the area of field sampling and/or analytical methods.

SECTION 5

DECONTAMINATION METHODS FOR MOBILE RESPONSE EQUIPMENT

INTRODUCTION

Chemical and physical properties of the substances in the water or soil under treatment are major considerations in designing procedures for decontaminating equipment. Decontamination involves removal and detoxification of the chemical substance. The selection and success of a single method or sequence of methods is determined by the substance's properties. Procedures for decontamination methods may be divided into three categories:

- Solubilization methods (use of solvents)
- Chemical degradation of surface contaminants
- Physical decontamination methods.

Each method uses a different mechanism to remove contaminants. They vary with regard to efficiency, safety, and cost.

The following sections discuss methods that may be employed to decontaminate a mobile response system. Both conventional and developmental state-of-the-art methods are reviewed.

SOLUBILIZATION METHODS (use of solvents)

In employing solubilization methods for the decontamination of the mobile response equipment, primary consideration must be given to the removal of contaminated soil particles or oils that have been deposited on the equipment throughout the cleanup process; these substances may contain an unknown amount of contaminant. Applying solvent formulations, aqueous or not, typically involves immersion or spray (flushing) techniques. Spray cleaning techniques are more suitable to decontamination of the mobile response system. Although the mechanisms and factors associated with the use of aqueous-based detergents and organic solvents differ, a typical scenario that outlines major steps in the decontamination sequence is as follows:

- Rinse the equipment with water to remove gross contamination
- Apply the solvent formulation
- Wait for the formulation to act

- o Rinse the equipment to remove contaminant and/or formulation
- o Treat/dispose of process fluids.

The actual sequence of steps will depend upon the solvent formulation used and the nature of the contaminant. Decontamination procedures that involve a combination of methods (i.e., use of aqueous and organic solvents) may require intermediate steps that allow the transition from aqueous to organic solvents. For example, if the surface to be cleaned is predominantly organic, an initial water rinse may impede the action of the solvent formulation by forming an aqueous film impervious to the solvent; it would thus prevent the TCDD and other organics from being dissolved. Final treatment and disposal of the solvent formulation is necessary as the contaminant has only been physically removed from the equipment; it still presents potential problems to the environment. Often the process fluids may be stored for later disposal by incineration. Another option is to subject the dioxin-contaminated material to chemical degradation methods; these methods completely eliminate dioxin and its hazards.

Detergents, Aqueous Surfactants

Adding detergents to water enhances its utility as a cleaning fluid in a number of ways. Water is effective as a rinse; as a cleaning fluid, however, it cannot remove hydrophobic contaminants, that is, contaminants that have no affinity for water. Detergents, specifically the surface-active agents, enable water or aqueous-based cleaning fluids to overcome this problem. Surfactants allow the contaminant and the cleaning fluid to interface, they promote wetting of contaminated surfaces and allow the cleaning fluid to spread over all surface recesses. Most important, they reduce or break the bonds linking the contaminant to the surface. The cleaning fluid is then able to "lift" the contaminant from the surface and hold it in liquid suspension. Cleaning is complete following the removal of contaminant and detergent in a rinse cycle.

The detergents Pennwalt 91 and Oakite have been effective in decontaminating pesticide barrels used for the storage of 2,4-dichlorophenoxyacetic acid (2,4-D), 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) or chlordane (19). The active ingredients of Pennwalt 91 are sodium orthosilicate and caustic soda. Oakite cleaner is a formulation of alkaline salts, primarily phosphates and carbonates, and synthetic surfactants. The detergents in prepared form were 1 to 2 percent caustic. These products are both alkaline anionic surfactants which require an elevated pH to promote saponification of oily materials. Results show that chlordane removal was 98 percent effective if the container was rinsed/thrice with water and washed with detergent (20). Triple rinsing alone as a single step removed at least 90 percent of the chlordane. Dioxin, like chlordane, is a chlorinated aromatic. It seems reasonable to assume that using Pennwalt 91 and Oakite cleaners would give comparable results for dioxin-contaminated surfaces; however, the selection of a feasible detergent may require site specific information about the nature of the contaminant before a suitable product can be selected.

The U.S. Army lists the commercial product, Gunk, as a decontaminant for equipment and vehicle exteriors (19). Various preparations for Gunk have been formulated for a number of cleanup problems. These are summarized in Table 2.

TABLE 2. GUNK DECONTAMINATION PREPARATIONS

FORMULATION	PRIMARY INGREDIENTS		USE
Gunk, I.S.	Water	>35%	Industrial shampoo and rust-retardant concentrate used for cleaning metal machinery
	Petroleum distillates	<25	
	Vegetable fatty acid soaps	>15	
Gunk, V.W.	Alkaline salts	<85%	Wash solution for automobiles and painted surfaces
	Synthetic wetting agents	>15	
Gunk, G.P.	Petroleum distillates	<70%	Degreaser for use on garage floors and power mowers
	Water	>10	
	Vegetable fatty acids	>9	
Gunk, C.D.	Caustic soda	<70%	Corrosion digester for cleaning tanks
	Organic chelating agents	<35	

Using one or more of these formulations to successfully decontaminate the mobile response equipment seems promising. The establishment of optimal pH and concentration ranges for these or any detergent formulation can only be beneficial to the effectiveness of a decontamination procedure (21).

A likely candidate for use may be Alconox, a common laboratory detergent whose primary ingredients are hydrocarbon sulfonates and complex phosphates. A standard household bleach like Clorox might fit into a decontamination sequence. Clorox is a 5.25 percent solution of sodium hypochlorite in water, which may be corrosive to metals. The availability of these two cleaning fluids is an obvious advantage.

Organic Solvents

Selection of an efficient solvent is based on its ability to become miscible with the contaminant, following the general rule of "like-dissolves-like." In other words, if the hydrogen bonding potential of a contaminant is identical or similar to that of the solvent, solubilization and removal of the contaminant will be ensured. As the difference between contaminant and solvent increases, the effectiveness of the solubilization mechanism becomes more limited. The use of organic solvents to decontaminate equipment is especially effective when films or coatings of grease and oil are present. Care must be taken in selecting organic solvents. They may damage certain surfaces like plastics, once the contamination layer is removed. Safety and flammability, along with reactivity of the solvent with the contaminant, are factors that should be considered.

Organic solvents in liquid form may have limited use in an incinerator decontamination process. Unless they are extremely viscous, liquids tend to run off vertical surfaces before they completely penetrate the contaminant. Gels, foams, or pastes which have the ability to cover, adhere to, and dissolve a contaminant layer deposited on a surface show promise as acceptable solutions to this problem. These foams weaken or destroy the link between contaminant and surface, and also produce lower volumes of waste (11). Foams are usually generated from acid and air, nitrogen or inert gas. Various chemical additives such as inhibitors, foam stabilizers, and surfactants are added. Gels may be either organic- or inorganic-based systems containing decontaminating chemicals such as acids. Problems may arise if the decontaminating chemicals inhibit generation and maintenance of a gel medium. Pastes usually consist of a filler, a carrier, and acids combined to give an appropriate consistency.

Application methods vary among the three. Foams can be pumped through pipes or sprayed on external surfaces. Gels are generally applied to external surfaces. Internal surfaces of removable parts can be cleaned by dipping them into the gel. Pastes are currently used on external surfaces and applied by hand; however, spraying techniques may be possible if the appropriate paste consistency is formulated. Of the three techniques, only use of foams produces low worker exposure.

Foams can be applied internally by pumping and externally by remote spraying. Applications of gels and pastes are done manually and expose the worker to their ingredients. Neither gels nor pastes have been sufficiently studied to properly evaluate them technically or economically, but they appear promising. Foams have been tried on a larger scale and found to be a simple operation generating minimal quantities of waste while using simple equipment.

The removal of contaminant and solvent, may be achieved using a rinse cycle. Foams are often removed by wet vacuuming followed by water rinsing with reasonably small volumes of water. Collection of all wash and rinse solutions is necessary if the contaminant is not chemically altered to a non-hazardous form. If the solvent selected is volatile, a temporary structure

to house the decontamination procedure should be built to prevent the vaporized solvent from spreading to other sites. The enclosure design should include proper ventilation to eliminate risk to personnel. Upon completion of the equipment decontamination, the structure itself should be disposed of by appropriate means, such as incineration.

In the following discussions, consideration is primarily given to cold cleaning solvent application. Cold cleaning implies that the solvents are used at ambient temperatures. They may be sponged or sprayed onto the contaminated surface. Following application, the solvent sets on the surface for a period of time and is subsequently removed in a rinse cycle or by evaporation. Vapor degreasing, an alternative cleaning method that depends on solvents, does not appear to be an operation readily adaptable to large-scale cleaning needs. It uses vapors from a heated solvent for cleaning and usually requires that the contaminated item be placed inside a tank for treatment.

There are a number of liquid organic solvents commonly used to degrease industrial equipment. These solvents effectively remove dirt and oil layers that have been deposited on equipment surfaces. Three standard solvents used are trichloroethylene, 1,1,1-trichloroethane, and perchloroethylene. Trichloroethylene and 1,1,1-trichloroethane are the major solvents used in vapor degreasing and cold cleaning operations, respectively (22). Vaporization of the solvent is a factor to consider, especially when using trichloroethylene (b.p. 57°C). It may be necessary to temporarily enclose the decontamination procedure to contain these solvent vapors.

Studies on decontamination by the Bendix Corporation in Kansas City, Missouri, identified several liquid organic solvents that removed grease from surfaces (23). The surfaces were subjected to a solvent rinse before analysis. Three solvents representative of a moderate hydrogen-bonding class were shown to remove a limited amount of contamination. It is believed, however, that improvement of contamination removal is possible if the surfaces are allowed to remain in contact with the solvent for a longer period of time, or if multiple rinses are performed. The solvents used were 1,1,2-trichloroethane, 2-ethyl-hexyl acetate, and acetone. Heptane, a non-hydrogen-bonding solvent, also removed a limited amount of contaminant after one solvent rinse.

Decontaminants used by the U.S. Army for removing chemical and/or biological agents from vehicle exteriors and equipment include a number of organic solvents that might be useful in decontaminating the mobile response equipment (19). Alcohol, diesel fuel, and naphtha are among those. Specific organic solvents included: BPL (beta-propiolactone), carbon tetrachloride, formalin-methanol, monoethanolamine (10 percent aqueous solution), and perchloroethylene. In addition, a solvent solution of hexachloromelamine (8 percent) in 1,2-dichloroethane may have potential use.

Formulation of a hydrogen-solvent-based dispersant/gelling agent mixture has been achieved for the cleanup of structures contaminated by oil spills (24). The dispersant and gelling agent are mixed in storage drums in a volume ratio of 4 to 1. The gelling agent selected, Triton X-100, was evaluated

according to efficiency and nature of toxicity. Approximately 30 dispersants have been approved for use with this gelling agent by the Warren Spring Laboratory, Stevenage (England); these are licensed by Britain's Ministry of Agriculture, Fisheries, and Food. The gel is produced in and delivered to the contaminated surface using a spray gun. The spray gun is designed to mix two independent feed trains prior to delivery as one stream from a flat jet nozzle. The gel is applied as a thin film over the contaminated surface and allowed to set. The gel mixture itself is stable for about 24 hours; however, stability may be lost after a shorter time depending on temperature conditions. After a sufficient amount of time, the surface may be rinsed off. The wash solution must be collected and disposed of by appropriate methods. Decontamination should be complete after a single treatment, but excessive contamination may require a second application.

Health Physics, Inc., a subsidiary of Quadrex, has developed a copolymer that shows potential for use in the decontamination of equipment surfaces. The copolymer, Quadcoat, is sprayed onto a contaminated surface where it reacts with the particles or residues present. The polymer dries, loses its adhesive character, and shrinks. It and the absorbed contaminant are then removed by hosing down the equipment. The polymer has a notable advantage over liquid solvents because it could be applied to vertical as well as horizontal surfaces. The effectiveness of Quadcoat as a decontaminant is dependent on its contact with the unwanted materials.

When selecting a solvent it is also important to select a "safe" solvent. It is not good practice to use a solvent that may be almost as hazardous as the contaminant itself. A safe solvent, such as 1,1,1-trichloroethane, should have a high flashpoint (or no flash point), a low evaporation rate, and a high threshold limit value (TLV). Solvents such as carbon tetrachloride (low TLV), acetone (low flash point), or formalin (suspected carcinogen) are not good choices since the risks to the workers may be high (EPA Peer Review, 1985).

Steam Cleaning

High-pressure steam cleaning methods are often effective in removing surface contamination (11). The production of large volumes of wastewater such as those generated by flushing methods is avoided; often the method is simply an easier or quicker procedure. The pressure of the steam as it is delivered to a contaminated surface is the primary mechanism for successful removal. Detergents or chemicals may be added to facilitate removal of contaminants that tightly adhere to equipment surfaces. The chosen additives are mixed with steam and entrained to form a single stream that is discharged onto the contaminated surface. Although the steam is delivered under high pressure, the low density of the cleaning fluid demands that the steam nozzle be positioned within a few centimeters of the contaminated surface. Supplied pressures for steam are typically 6.1 to 6.8 atm; discharge of the steam through the equipment and out the nozzle usually results in a 15 percent reduction of the supply pressure. Rates for the discharge of detergents are

approximately 200-300 l/hr.

The equipment is commercially available and has been used in various applications (11). It is also a fairly low-cost method. Its effectiveness depends on the specific application. The spread of contamination is perhaps the primary factor to consider, especially where the removal of hazardous substances is concerned; the impingement of the steam jet can redistribute the contaminant. Containing the cleaning procedure in a temporary structure has been suggested as a feasible solution to this problem. Following the removal of the decontaminant from the equipment, the enclosure must be thoroughly cleaned. Care must also be taken while using steam cleaning equipment. For obvious reasons, the temperature and pressure conditions of the steam can be hazardous to personnel. In addition, visibility may be limited if condensing steam produces fog during the cleaning operation. It is recommended that respiratory, eye, and skin protection as well as thermally insulated gloves be used during the procedure.

This type of treatment is not recommended where the contaminants may volatilize, creating a hazardous condition for the workers and the surrounding environment. Using a water blaster (hydrolaser) to physically clean the surface by applying water pressure to the contaminated equipment is a better technique in this situation.

Chemicals (High/Low Concentration)

Many chemicals are acceptable for decontaminating exterior locations (such as concrete and metal) and interior structural members (such as painted surfaces or concrete). "Decontamination" as defined in the context of these chemical processes is removal of superficial dirt and oxides from surfaces. Most of these chemical methods seem applicable for dioxin decontamination of the mobile response equipment because dioxin accumulates on the equipment's surface (25). Some chemical methods are highly corrosive to the surface. Acids and alkalis are used to dissolve metal from the surface; complexing agents are used to enhance the dissolution. Significant corrosion is normally acceptable for equipment that is decommissioning; this is not desirable for mobile response equipment.

Generally, solutions with greater than 2,000 ppm (0.2 percent) of reagent are classified "high concentration." "Low concentration" solutions contain less than 0.2 percent reagent and normally less than 0.1 percent. Some complexing agents are also discussed in this section. The solubility of the metal from the surface being cleaned increases due to the formation of the complexes, which enhances their removal from scales, deposits, or corrosion films. For example, triethylenetetramine hexaacetic acid (TTHA) and hydroxyethylenediamine triacetic acid (HEDTA) complex with heavy metal ions such as cobalt, nickel, iron, chromium, and many other di- and trivalent ions. Citric acid, citrate, oxalic acid, oxalate, ethylenediamine tetracetic acid (EDTA), and phenylthiourea components of the decontamination reagents described below can all form metal ion complexes. Although these complexing agents are not effective in complexing most organic compounds, they can be valuable in removing a thin-layer surface metal and/or metal oxide, thereby releasing the

contaminants (e.g., dioxin) deposited on the surface of the mobile response equipment.

Many chemical decontamination processes used to decontaminate metal surfaces in nuclear power facilities are listed below (25). The process for Inconel and carbon steel are listed first because the solids ram feed system, ash chute, and kiln-secondary combustion chamber (SCC) duct are made of Inconel, and the rotary kiln and the SCC are made of carbon steel.

Reagents for Inconel Decontamination

High Concentration Reagents-

- Conditioning with alkaline permanganate (AP) at 90°C to oxidize the corrosion product film. After water rinsing, treatment with 0.4M ammonium citrate (AC). AP is 2.5M NaOH + 0.2M $KMnO_4$.
- Treatment with AP as in above followed by oxalic acid.
- Treatment with AP and oxalic acid as above followed by treatment with AC. AC prevents redeposition of oxalate precipitates.
- Conditioning with AP as above followed by treatment with citrox (0.2M citric acid + 0.3M oxalic acid). Citrox neutralizes any traces of the alkaline solution, dissolves any manganese dioxide residue, and complexes the iron oxides to keep them dissolved and prevent redeposition.

Low Concentration Reagents-

- Treatment with chelating agents such as EDTA, citric acid, or oxalic acid.
- Treatment with hydrogen peroxide in low ppm concentration range at temperatures less that 70°C. This process does not solubilize iron.
- Treatment with a mixture of oxalic acid (2-3 g/l) and hydrogen peroxide (50 g/l) at 80°C. Also effective for decontamination of carbon steel.

Reagents for Carbon Steel Decontamination

- Treatment with HCl-containing inhibitors like propynol formaldehyde. Typical suggested concentrations for HCl and inhibitor are 15 percent and 1 percent by volume, respectively.
- Treatment with 0.4M ammonium oxalate and 0.16M citric acid and 0.3M H_2O_2 at 90-95°C. Citric acid complexes the iron ions and prevents formation of insoluble oxalate.

- Treatment with 0.5 percent solution of EDTA, citric acid, and hydrazine at pH 6-8 and temperature 90-100°C.

- Treatment with inhibited AC or sodium bisulfate.

- Treatment with inhibited 9 percent sulfamic acid (NH_2SO_3H). Typical inhibitors are 5 percent solution of formaldehyde or propynol.

- Treatment with 0.3M H_2SO_4, 0.1M oxalic acid, and phenylthiourea (sulfox) at 25°C for 40 minutes.

- Treatment with phosphoric acid (90-130 g/l) at 85°C for less than 20 minutes. Redeposition occurs if acid is left in contact with base metal for more than 20 minutes. The process is mildly corrosive.

- Treatment with "new solvent" NS-1 (a proprietary product of Dow Chemical Company).

- a) Water rinse

  b) Scrub with 10 percent citric acid and 5 percent detergent

  c) Scrub with 0.3M citric acid, 0.1 percent detergent, and 0.5M HCl rinse

  d) Scrub with 6M HNO_3

  e) Repeat d) as necessary.

- Treatment with 0.002M HEDTA, 0.002M citric acid, and 0.002M ascorbic acid at pH 2.6.

- Treatment with 0.002M HEDTA, 0.002M citric acid, plus 0.004M hydrazine at pH 3.3.

- Treatment with 0.002M HEDTA, 0.002M citric acid, plus 0.012M hydrazine at pH 7.

Reagents for Oil and Grease Removal

- Treatment with 1 wt. % Lissapol (nonionic wetting agent), 1.2 wt. % sodium carbonate, 2 wt. % sodium tripolyphosphate, 0.1 wt. % sodium carboxymethylcellulose, plus 0.5 wt. % EDTA at pH 9.5.

- Treatment with 1.5 wt. % Comprox (anionic wetting agent), 2.5 wt. % sodium sulfate, 0.6 wt. % sodium carbonate, 2 wt. % citric acid, 1 wt. % EDTA at pH 3 and temperature of 70°-80°C. This solution attacks metal.

For a number of other processes listed by Nelson and Divine (25), the long periods (many hours to days) of chemical application are specifically mentioned. Because applying those methods to the surface of the mobile response equipment is difficult in practice, they are not listed here. The application time for the methods listed here is not specifically mentioned in the literature (25). The high concentration chemicals probably require short chemical application periods to decontaminate the surface of the mobile response equipment. Maintaining high temperature for short periods would be practical. Dilute solution processes, which are effective only when applied for long duration, have limited use for decontaminating the mobile response equipment.

The reagents presented in this section vary in their rate of attack on metal surfaces. Deciding which reagent to use for a particular purpose will depend on the metal being cleaned and its degree and nature of contamination. The availability of the ingredients, their cost, and their handling hazards must also be considered. The wide variety of reagents facilitates choosing one suitable for the specific application.

Summary of Solubilization Methods

Decontamination methods that utilize solubilization techniques are very effective in removing surface contaminants (See Table 3); however, they are limited in detoxifying hazardous chemicals unless the cleaning fluid or operating conditions (i.e., high temperatures) specifically degrade the chemical. Using detergents in cleaning procedures is common and relatively simple, and it presents minimal safety problems to personnel.

Various detergent formulations are available for removing dirt or oil layers, the typical mediums containing contaminants. Cleaning procedures that use organic solvents have a number of limitations. The solvents may be toxic when inhaled, easily volatile, and/or flammable. They may also damage certain nonmetal surfaces such as plastic-coated pieces. The development of gels, pastes, and foams reduces some of these problems which are especially associated with liquid organic solvents. A semi-solid form such as a gel formulation shows potential if an appropriate (effective) formulation is available. High-pressure steam cleaning does not demonstrate applicability to the mobile response systems because the dangers associated with the spreading of contaminants are too great.

CHEMICAL DEGRADATION OF SURFACE CONTAMINANTS

Degrading a contaminant to a less hazardous substance greatly reduces the spread of contamination inherent in the removal of the contaminant from the equipment. This essentially eliminates the problems associated with the generation of contaminated wash solutions. At present, the majority of degradation techniques require contaminant removal from a surface followed by treatment in a reactor or laboratory setup. Chemical degradation, in this regard, is the final step in the decontamination process.

TABLE 3. SUMMARY OF SOLUBILIZATION METHODS FOR REMOVAL OF SURFACE CONTAMINATION

	FOAMS, GELS, AND PASTES	DETERGENTS, AQUEOUS SURFACTANTS	ORGANIC SOLVENTS
REMOVAL OF BASE METAL	None-Slight	None	None-Slight
AREA OF APPLICATION	Internal/ External	Internal/ External	Internal/ External
QUANTITY OF WASTE PRODUCED	Small	Large	Moderate
WORKER EXPOSURE	Foam: low Gels & Pastes: Moderate	Moderate	Moderate
OVERALL COSTS	Moderate-High	Moderate	Moderate-High
COMMENTS	Gels and pastes cannot be easily applied to the inside of small diameter pipes	Formulations may be tailored to specific contaminants	May be flammable,and/or damage non-metal surfaces. Limited effectiveness on vertical surfaces

Destruction of dioxin has, in general, been a large problem because of its persistence in the environment and its apparent unreactive nature. Recent laboratory and field work show that dioxin and similarly-structured chlorinated aromatics such as PCBs and DDT may be amenable to chemical degradation. Degradation's primary object is to convert the toxic compound to a less hazardous form or to a compound which exhibits a greater degree of solubilization in, for example, a solvent employed in the decontamination procedure. Ideally, the degradation step should be incorporated in the pretreatment routine.

The following sections review and discuss the various chemical degradation methods available (See Table 4). Emphasis will be placed on those methods that show promise for in-situ decontamination operations.

Oxidation

Oxidation, as with most of the chemical degradation methods, is a single step in the general decontamination process. Its role in the pretreatment or final detoxification stage depends on the product to be obtained and the method to use.

Tetrachlorodibenzodioxin (TCDD) in carbon tetrachloride has been oxidized by ruthenium tetroxide in laboratory operations (26). An excess quantity of the oxidant is supplied to limit the number of reaction intermediates. The reaction efficiently utilizes ruthenium tetroxide. Following the completion of an oxidation step, a secondary oxidant is formed. The presence of the secondary oxidant lessens the demand the reaction intermediates place on the primary oxidant.

The reaction follows first-order kinetics with a reported half-life of TCDD of 560 minutes (20°C). It is advisable to proceed using a continuous reflux of carbon tetrachloride; this reduces the half-life of TCDD and thus speeds up the oxidation process. In addition, the rate may be increased by raising the temperature during the reaction. Specifically, a temperature increase to 70°C results in a half-life of 15 minutes (27). Ruthenium tetroxide is a powerful oxidizing agent and must be used with solvents of electronegative character. Oxidative control of TCDD degradation has been limited to laboratory work. Studies on a larger scale should define the operating conditions and lend evidence to the feasiblity of extending this technique as an in-situ method.

Hydrodechlorination

Hydrodechlorination is a means of decontamination that appears to readily adapt to PCB, DDT, and dioxin contamination problems. The nickel-catalyzed reaction is carried out in ethanol; sodium hydroxide is present and functions as an acid-acceptor. As the reaction proceeds, aromatic chlorine atoms are removed one by one, thereby reducing the hazardous potential of the chlorinated compound to an environmentally acceptable product. Laboratory-scale hydro-

TABLE 4. SUMMARY OF CHEMICAL DEGRADATION METHODS FOR REMOVAL OF SURFACE CONTAMINATION

	HIGH INTENSITY LIGHT	UV LIGHT CLEANING	ELECTRO POLISHING
REMOVAL OF BASE METAL	None	None	Can be carefully controlled
AREA OF APPLICATION	External	External	External/ Internal
QUANTITY OF OF WASTE PRODUCED	Small	Small	Moderate
WORKER EXPOSURE	Low	Low	Moderate
OVERALL COSTS	Low-Moderate	Low-Moderate	Moderate-High
COMMENTS	Most effective on flat surfaces	Gross contamination must be removed first for UV to be effective	Contaminated object must be immersed in a liquid bath

chlorination of PCB and DDT shows successful conversion of the parent polychlorinated compounds to molecules that contain at most one chlorine atom (28). The Sun Ohio Process which follows this reduction principle has been used for several years to remove chloride ions from dielectric fluids containing PCBs. The endproducts are sodium chloride and trichlorobenzene (EPA Peer Review, 1985).

Although studies have been limited to laboratory reactions for dioxins, hydrodechlorination shows potential for development as an in situ operation. The solvent could be applied to the contaminated surface, allowed to degrade the dioxin present, and then be removed in a rinse cycle.

Application of the procedure to dioxin deserves some investigation.

Photochemical Reduction

Photochemical reduction shows adaptability as a decontamination method for in situ operations. Three conditions must be met for photochemical reduction: 1) the compound must be able to absorb light; 2) light must be supplied at the proper wavelength and intensity; 3) and a hydrogen donor must be present (29.) The hydrogen donor, present as a solvent, could be applied directly to the contaminated surface of the mobile response equipment. A suitable solvent should be relatively nonvolatile and nontoxic. Expense and availability are other concerns. Once applied, the solvent would interact with the contaminant in the presence of UV light. The final step in the sequence would be the removal of the solvent from the equipment in a rinse cycle.

Various studies support the idea of photochemical degradation of dioxin. Field experiments using a 2,4-D/2,4,5-T ester formulation (.02 ppm TCDD) resulted in a 50 percent decrease of TCDD after one day; TCDD was undetectable after the second day (29). In Seveso, Italy, the application of an olive oil solution to small plots of TCDD-contaminated grassland effectively destroyed 90 percent of TCDD after nine days in sunlight. Laboratory studies show a 50 percent reduction after six hours. These studies involved the irradiation of thin films of TCDD placed on glass plates (30).

Although an in-situ operation is the ideal, removing and subsequently treating dioxin-contaminated rinses is an acceptable alternative (31). Circulation of these rinses through a UV-irradiated tank would be relatively simple. High pressure water cleaning used in conjunction with photochemical reduction ideas may be an acceptable method. However, soil particles or oil may interfere with the absorption of light by TCDD. This could be a significant problem that should be considered in developing the decontamination procedure.

Another inherent problem is the availability of sunlight. Obviously, sunlight is limited during certain seasons of the year. Using commercial UV lamps may be an alternative. Selection of a commercial light source, if necessary, will most likely be dependent on effectiveness (i.e., wavelength range), safety (i.e., voltage requirement), and cost.

Flash Cleaning

Flashlamp cleaning systems developed by Maxwell Laboratories, Inc., have been employed to clean and remove surface coatings on industrial equipment (32). The system is acceptable to the environment, shows versatility in removing a variety of substances or materials, and performs localized cleaning only. In addition, flash cleaning systems can selectively remove one or more surface layers. Methods of cleaning using flashlamp systems are comparable to those using laser radiation with one exception: cost; flashlamp systems are much less expensive.

Maxwell Laboratories, Inc., has developed a high-intensity light source (lamp) using xenon gas-filled tubes that are able to deliver short pulses. These lamps are marketed under the trade name "Flashblast." Decontamination is affected by placing the lamp on the contaminated surface and initiating the firing or blasting sequence. The emitted radiation extends from the ultraviolet to the beginning of the infrared; more than half is emitted in the UV. Flash cleaning is limited because it needs a relatively flat surface to be effective. Removal depends on the contaminant and the treatment conditions. The contaminant may be photochemically reduced, vaporized, incinerated, or in the presence of water, "steam cleaned." Future studies may define more completely the mechanism specific to the contaminant.

The lamp can be hand-operated or controlled from a distance. Flashblast units are available in various sizes (33). The smallest moves easily and operates from a standard outlet (120 volts). If performed correctly, the procedure is not dangerous to the operator, although ear protection that guards against the loud noises produced by the system is highly recommended. Flash cleaning has been used to remove epoxy paints from equipment and to clean corroded steel surfaces (32). This latter process is aided by an application of 6 percent citric acid solution to the metal surface prior to irradiation.

A second flash cleaning technique, the pulsed ultraviolet (PUV) radiation system, is in the developmental stage. It also shows promise as a means to decontaminate the mobile response equipment. The system utilizes ultraviolet energy to chemically degrade the contaminant. The light source is more intense and richer in UV than in the xenon lamp systems. The mechanism for detoxification appears to involve pyrolysis, incineration, and/or photochemical reduction of the molecule. The radiation is delivered to the surface by high-intensity industrial PUV lamps. The surface temperature is rapidly raised to 2,760°C and the contaminant is destroyed.

Delivering the energy in short pulses minimizes damage to the surface; the rapid flash heating essentially eliminates vaporization of the contaminant. Higher intensities can be used to remove equipment coatings that have been contaminated by absorption. Although testing is not complete, PUV light has been effective in reducing the pesticide, malathion, to traces undetectable by GC/MS techniques.

Electropolishing

Electropolishing is a relatively simple process. Except for equipment for circulating or agitating the electrolyte, the systems have no moving parts and are amenable to remote operation and mechanization to minimize personnel exposure. The smooth surfaces produced by electropolishing are reportedly much easier to clean using standard decontamination techniques than are metal surfaces with a normal as-received finish.

The metal to be decontaminated is utilized as the anode in an electrolytic cell. The passage of electric current through the electropolishing system results in the dissolution and, under proper operating conditions, the progressive smoothing of the anode's surface. Contamination present on the metal surface and entrapped within surface imperfections is transferred to the electrolyte by the process. The amount of metal removed from the component surface is controlled by the duration of application, usually, less than 0.002 inches to affect decontamination. The surface metal is reportedly uniformly removed with no preferential attack of grain boundaries or other microstructural features.

After electropolishing, the metal should be rinsed with water, dried, and then painted. Phosphotizing the surface enables the paint to adhere better. If left uncoated, the highly active metal surface will corrode or oxidize, or the fine interstices will fill with physical contamination (EPA Peer Review, 1985). Studies have found the electropolished surfaces have better corrosion resistance than the original surface.

Because of its inherent stability, safety, and applicability to a number of alloy systems, phosphoric acid is generally used as the electrolyte. Due to its hygroscopic nature, phosphoric acid helps minimize airborne contamination. It is believed that the good complexing characteristics of phosphoric acid for metal ions is a significant factor in minimizing recontamination from the electrolyte. Other acids and chemicals have been added to the phosphoric acid electrolyte to enhance surface passivity, increase brightness, or promote sludging.

Summary of Chemical Degradation of Surface Contaminants

Most chemical degradation techniques show limited usefulness when they are extended to mobile response decontamination procedures (see Table 3), primarily because of the contaminants unreactive nature. The development of an in-situ operation using the mechanistic approach of oxidation or hydrodechlorination does not seem effective or cost-efficient. Photochemical reduction, also a developmental idea, shows promise as a simple, low-cost, effective operation. Its consideration seems unlikely at the present time, however, because the procedure has only been studied under laboratory conditions.

Flash cleaning is an innovative procedure primarily used for specialized cleaning operations. Its extension to the decontamination of the mobile

response equipment shows promise; the procedure is not dangerous, permits detoxification as well as removal, and exhibits selective and controlled removal of surface layers. A prime factor is the high degree of assurance that the contaminant has been effectively removed.

PHYSICAL DECONTAMINATION TECHNIQUES

A number of commercially available physical decontamination techniques have been identified and evaluated as to their potential for effective use. Ideally, the cleaning of any surface should meet the following criteria:

- Minimal exposure of personnel to the contaminants
- Minimal volume of secondary waste generated
- Minimal recontamination of previously cleaned surfaces
- Minimal off-site release
- Minimal manpower costs.

Selection of appropriate cleaning processes must also take into account the required degree of cleanliness, as well as the chemical and physical properties of the contaminant which determine the strength of adherence to the substrate. The physical decontamination techniques evaluated can be grouped into one of two categories: abrasive methods and non-abrasive methods.

ABRASIVE CLEANING METHODS

Abrasive cleaning methods are physical decontamination techniques which work by rubbing and wearing away the top layer of the surface containing the contaminant. The methods are generally very effective at removing the contaminant from the surface. The following sections review the abrasive cleaning methods available (see Table 5).

Mechanical Methods

Mechanical methods include using cleaning devices like brushes for cleaning the insides of pipes. The brushes may be composed of metal or nylon and are commonly blown through the pipe with water or air, or pushed through manually. The amount and type of contaminants removed will vary with hardness of the bristles, length of time of brushing, and the degree of brush contact with the pipe surface. Pipes with inside diameters up to four inches can be cleaned with brushes.

Another type of pipe cleaner is a bullet-shaped object known as a pig, which is forced through a pipe by fluid pressure (11). The pig is capable of scraping and abrading tightly held material off the wall of the pipe. Pigs

TABLE 5. SUMMARY OF ABRASIVE METHODS FOR REMOVAL OF SURFACE CONTAMINATION

	MECHANICAL METHODS (pigs)	MECHANICAL METHODS (brushes)	ABRASIVE CLEANING (wet)	ABRASIVE CLEANING (dry)	DRY ICE BLASTING
REMOVAL OF BASE METAL	Slight	Negligible	Can be carefully contained	Capable of severe abrasion	Negligible
AREA OF APPLICATION	Internal	Internal/ External	Internal/ External	Internal/ External	External
QUANTITY OF WASTE PRODUCED	Moderate	Moderate	Large	Large	Small
WORKER EXPOSURE	Low	Moderate	Moderate	High	Moderate
OVERALL COST	Low	Low	Moderate	Moderate	Moderate
COMMENTS	Flexible and compressible Cleans-small diameter pipes.	Wide range of brush sizes and bristle stiffness.	Removes tightly adhering material. No air pollution.	Dust may be explosive.	Useful for removing smearable contaminants.

are available with soft cores and tough, abrasive outer coatings. They are normally available for cleaning pipes with diameters from 2 to 150 cm., but can be obtained in diameters as small as 1 cm. The plastic-bodied pig is flexible enough to pass through 90° elbows and compressible enough to pass through reductions of 1 cm. in pipe size.

The equipment to perform these types of mechanical cleaning is readily available in a wide range of sizes. Brushes and pigs are relatively inexpensive and easy to use; further, they generate small amounts of waste material. They do, however, require physical access to both ends of the pipe being cleaned.

Air Blasting

Air blast equipment uses compressed air to force abrasive material through a nozzle at high velocities. The cleaning efficiency of this method is a function of a number of factors including: distance between the nozzle and the surface being cleaned; air pressure; length of time of application; and the angle at which the abrasive strikes the surface. The distance between the nozzle and the surface is important because the velocity of the abrasive particles decreases with distance traveled. The abrasive stream also diverges with distance traveled, resulting in weakened cleaning action. Air pressures used vary with the material being cleaned. Softer metals are cleaned with air pressures ranging from .7 to 4 atm while steel and concrete are cleaned at pressures of 5 to 6 atm (11).

Abrasive contact time is very important. If it is too short, the cleaning will be insufficient; if it is too long, excessive base metal may be lost, even to the point of wearing a hole through the object being cleaned. Generally, the abrasive stream should hit the surface steadily for not more than a few seconds. Tests should be conducted to determine the optimum cleaning time for each particular situation. Finally, if the angle at which the abrasive strikes the surface is too low, the resultant cleaning action will be insufficient. This can be a problem when trying to clean the inside of pipes or other objects.

Pipe lengths of up to 30 meters can be cleaned using flexible hose, which is capable of moving through one or more elbows (11). A nozzle can also be attached to the end of a gun and used to clean inside tanks. In addition, air blast cleaning has proven effective over years of use, especially in removing tightly-adhered material, and equipment for it is commercially available.

The system's disadvantages are its inability to closely control the amount of material removed and the large amount of waste that it generates. The contaminated dust can migrate from the work area and provide risk to the worker and the environment. Dry methods also create sufficient quantities of abrasive dust to require a collection and filtering system to clean the air. The most serious limitation is the uncontrolled toxic dust generated from blasting a dioxin-contaminated surface.

Wet Blasting

Wet blast cleaning, uses very fine abrasives ranging in size from 100 to 5,000 mesh, which is much smaller than that used for air blast cleaning (11). By using very fine abrasives, the amount of materials removed can be carefully controlled and the surface smoothness and dimensions of precise equipment maintained. Water is used at pressures as high as 300 to 600 atm. The combined effects of both the water and the abrasive produces a stronger cleaning action than can be obtained with water or dry abrasives alone (11). Wet sand abrasive cleaning costs $25-$35 per m^2 (Norman Higgins, Eastern Cleaning Equipment, personal communication, 1984).

The abrasive is suspended in water by an agitator. Compressed air and nozzles, as in air blasting, deliver the abrasive/water mixture to the decontamination area. The nozzle's lifetime may need to be considered; the abrasive action of water-driven particles is more severe than that of air-driven particles, therefore the nozzle wears out faster (11). Careless application may produce excessive wear of metal surfaces, so careful control is necessary.

Water abrasive blasting is more effective in cleaning recesses and produces a smaller amount of waste then air abrasive cleaning. It will remove tightly-adhered material and corrosion layers and produces less dust than dry blasting methods. Destruction of the abrasive forms fine sand particles, which must be cleaned off surfaces by rinsing or vacuuming.

Another variation of wet abrasive cleaning is air slurry blasting. As much as 30 percent (by volume) of abrasive is mixed with water to form a slurry, which is propelled by 6 atm of air. The rate of flow is adjustable, which in turn adjusts the cleaning action. Different cleaning effects can also be obtained by changing the type and size of the abrasive. Testing to determine the optimum slurry composition is required.

Slurry cleaning can also be adapted to clean the interior of a piping system. This method would be particularly useful for cleaning small diameter pipes (15 centimeters and under) and associated valves and fittings (11). Additional equipment would be required to recirculate and pump the slurry, and a reservoir of extra slurry would be necessary (11). As with any abrasive blasting operation, residual dust or abrasive particles may adhere to metal surfaces and should be removed by flushing the piping system.

Abrasive Materials

The different abrasives can be grouped into the following three general classes based on hardness of the abrasive material: soft, intermediate, and hard.

Soft abrasives include wheat grains, corn cobs, crushed nut hulls (such as walnut or hickory), rice hulls, and fruit pits (36). Soft abrasive cleaning removes only loosely held, smearable contamination without marring the surface. Air alone propels the abrasive. Because considerable amounts of dust or powder are produced, soft abrasives are not highly recommended for removing toxic contaminants unless the operation is enclosed.

Intermediate abrasives are harder than soft material, yet the cleaning action is gentler than that obtained with hard abrasives. The principal material in this category is manufactured glass beads (11). They can be used to clean precision parts. Although they produce less dust, they are still breakable, so their longevity is limited. Glass beads are more expensive than naturally occurring mineral abrasives and probably aren't much more desirable than other types of abrasives.

Hard abrasive materials are harder than the material being removed. They may be subdivided into naturally occurring minerals, synthetic minerals, and metal pellets. Natural abrasives consist of materials such as sand, crushed rock, garnet, pumice and emery (36). By far, sand and crushed rock are used in the largest quantities; use of the latter three is limited. When used in high-velocity blasting operations, garnet, pumice and emery disintegrate rapidly, withstanding only a few passes. Large amounts of dust are produced when these materials are used in air blasting; when used with water, the fine particles cause a cleanup problem.

Synthetic mineral abrasives include silicon carbide and aluminum oxide, which are man-made in electric furnaces (36). These abrasives are more resistant to breakdown than sand, but less resistant than metallic shot. Their use is limited because the initial cost is higher than most naturally occurring minerals.

Metallic abrasives have the highest initial cost of those abrasives discussed. They are available in two general types: grit and shot (11). Grit consists of angular metal particles composed of hardened cast steel or white cast iron. Shot is normally made of the same materials as grit, but it is spherical in shape. Shot may also be made of small cut pieces of steel or aluminum wire for cleaning soft metals. Both grit and shot have a relatively long life and are capable of being cleaned and reused more easily than any of the other abrasives.

Metallic abrasives produce very little dust, resulting in fewer airborne particulates. The rounded shot particles are less abrasive than the angular grit particles and tend to produce a peening action which could deform thin metal structures. Metallic abrasives are not recommended for cleaning mobile response equipment because of the high initial cost. After decontamination, the waste abrasive must be disposed of to prevent spread of contamination.

In summary, the size and composition of abrasives determine their cleaning effectiveness. The cleaning action of coarse abrasives is difficult to control and may produce rough surfaces, which are more susceptible to future contamination. Large particles clean more rapidly than small but may produce a peening action which could result in deformation of the surface being cleaned. On the other hand, abrasives that are too small may clean very slowly but produce less surface damage. The selection of an abrasive to do a particular job should be based on testing which identifies the size, shape, and pressure that produces a good balance of cleaning action and minimal surface damage.

Dry Ice Blasting

Using dry ice pellets as an abrasive is considered unique enough to justify discussing it separately.

Dry ice pellets are obtained by allowing liquid CO_2 to expand through a nozzle to one atmosphere of pressure. Some of the CO_2 released will condense into snow which can be compressed and formed into small pellets, approximately 0.3 cm. in diameter, and used as an abrasive (11). A high-velocity jet of air and abrasive is then directed onto the surface being cleaned. The resultant mixture of abrasive and contaminated materials will dissipate as the dry ice sublimes into gaseous CO_2, leaving behind only the contaminated material which can be vacuumed. While reducing the amount of wastes lowers disposal costs, equipment costs would be more than with ordinary abrasive blasting because special equipment is needed to handle and store the cold, pressurized, liquid CO_2 and a pelletizer. However, the overall cost is moderate and less than many other methods.

Dry ice blasting is still experimental and has seen only limited industrial use. It appears to be very useful for removing smearable and less tightly fixed contamination without abrading metal surfaces. The equipment being decontaminated should be enclosed to prevent the minimal spread of airborne contamination. Following decontamination, additional surface treatment to remove residual particles would be unnecessary.

NON-ABRASIVE PHYSICAL CLEANING METHODS

Non-abrasive cleaning methods are physical decontamination techniques which work by forcing the contaminant with pressure off of the contaminated surface. In general, less of the metal is removed using non-abrasive methods than abrasive methods. The following sections review the non-abrasive cleaning methods available (see Table 6).

High-Pressure Water

This cleaning system consists of a high-pressure pump, an operator-controlled gun with directional nozzle, and an associated high-pressure hose. Common operating pressures are from 340 to 680 atm, with resulting flow rates of 20 to 140 lpm (11). Pressure increases do not always enhance decontamination. The pressure needs to be high enough to remove the contaminant from the surface without damage. One study reported that 200 atm was the optimum pressure for physically cleaning vehicles (34). Pressures above a couple hundred atmospheres start to remove paint, but even pressures higher than 700 atm can be used without damaging the surface. One way to prevent impact damage on a surface is to keep the jet moving rapidly over the surface at oblique angles.

Nozzle diameter and shape also affect cleaning efficiency. Fan shaped nozzles produce a spray, while round nozzles produce a jet. Fan nozzles can be the most effective system if cleaning distance is less than 30 cm, but remote cleaning, which minimizes worker exposure, is preferable. Round nozzles are more efficient for distances beyond 30 cm or when a solid jet nozzle is oscillating at a relatively high frequency (34). Rigid controls necessary to ensure optimum jet generation from a nozzle are often not followed. For example, self propelling mole nozzles are attached to a flexible high-pressure hose which can bend near the nozzle, restricting proper flow. A minor factor like this has a major effect on diminishing the jet's cleaning efficiency.

Cleaning efficiency may also be dramatically affected by the addition of a chemical to the water jet. Chemicals can be added to prevent readhesion of material mechanically removed from a surface, to enhance decontamination of areas in which the jet has difficulty penetrating, and to leave a low surface tension film after liquid cleaning (34). The corrosivity of these additives must also be taken into consideration on a case-by-case basis.

High-pressure technology is well developed and has been used for many years; most parts are easily accessible, thus reducing downtime for maintenance and repair. It is adaptable for decontamination of various pipe sizes, equipment, and large planar surfaces. Associated costs should be relatively low compared to other decontamination methods (11). Application costs of cold, high-pressure water with a degreaser range from $15 to $20 per m^2 (Higgins, 1984). If the water is not filtered and recycled, a large amount of contaminated water is generated, thereby increasing costs.

Well-bonded surface contaminant films may not be removed by high-pressure water cleaning. It may be necessary to protect clean areas from back-splash of contaminated water. The direction of the stream of water must be controlled to avoid injury. For safety reasons, a valve is generally placed in the gun so that if the operator trips or loses control, releasing the trigger will redirect the spray though a large opening.

Ultra-High-Pressure Water

This system is capable of producing a water jet ranging from 1,000 to 4,000 atm (11). Ultra-high-pressure sprays can remove tightly-adhered surface films by force of the water. Above 2,000 atm, flexible hoses are not used and hard piping is required. The velocity of the water ranges from greater than 500 m/sec at 1,000 atm to 900 m/sec at 4,000 atm. The water can be discharged through a single nozzle or an array of nozzles. Cleaning the inside of a pipe is similar to highpressure cleaning, but due to the hard piping, careful design and reduced flexibility of the system are a concern when a pressure greater than 2,000 atm is used. Additives can be used to enhance the decontamination action. Another alternative is to add small quantities of abrasive material to the less-than 2,000 atm systems. This technique has been found to be four to five times more effective than using only water at the same pressure (11).

Ultra-high-pressure cleaning is no more effective than high-pressure cleaning on many hard, dense, and metal surfaces; however, it does surpass high-pressure cleaning in removing contaminants that adhere tightly to or are diffused into the surface. Primary application of the ultra-high-pressure water jet appears to be for decontamination of concrete surfaces and easily accessible metal surfaces. Removal of 1.5 to 3 mm of surface material occurs easily at 2,000 atm. The cost of using a water cannon to remove surficial concrete is $\$200/m^2$ (35). Concrete surfaces can also be removed by using a spaller, which consists of a hydraulic cylinder, a push rod, and a bit with expanding wedges. Associated costs range from $\$32/m^2$ for platform mounted models, to $\$40/m^2$ for hand-held models (35).

The basic equipment is commercially available, although the initial capital investment is quite high. Waste generation can be kept to a minimum by recycling wastewater. Equipment is available that surrounds the water jets and captures the water spray, minimizing overspray. Ultra-high-pressure water may be a very useful method for removing extremely tightly-adhered contaminants from concrete or other porous-type surfaces, such as wood. Although high-pressure water systems are the first choice for decontaminating dense metal surfaces, ultra-high-pressure systems should be used when the decontamination requirements exceed the capability of high-pressure water, for instance, when the contaminant has diffused into the metal.

High-Pressure Freon Cleaning

FREON cleaning has proved to be a very effective method for cleaning cloth, plastic, rubber, and external and internal metal surfaces. FREON 113 (trichlorotrifluoroethane) is relatively dense, chemically stable, non-toxic, non-flammable, and has a high dielectric value (11). It has low surface tension and leaves no residue. The vapor is easily removed from the air by activated charcoal. A high pressure (1,000 atm) jet of liquid FREON 113 is directed onto the surface to be cleaned. The FREON is collected in a sump, filtered, and then reused.

Health Physics, Inc. of Gainesville, Florida, is currently developing and experimenting with the design for a FREON 113 decontamination unit, large enough to accommodate a tank, that could be set up on site. Testing results have indicated that this method is capable of removing PCB residue and combustion products from internal and external surfaces (Karl Ashley, Health Physics Inc., personal communication, 1984). Smaller decontamination chambers are commercially available (11).

Special care must be taken to collect and reuse FREON as it is relatively expensive. If the air inside an enclosure saturated with FREON vapor is collected and cooled to condense the FREON, almost all of the FREON can be recovered.

TABLE 6. SUMMARY OF NON-ABRASIVE PHYSICAL CLEANING METHODS FOR REMOVAL OF SURFACE CONTAMINATION

	HIGH PRESSURE WATER (200-700 atm)	ULTRA HIGH WATER (1,000-4,000 atm)	HIGH PRESSURE FREON	ULTRASONIC	VACUUM
REMOVAL OF BASE METAL	Negligible	Slight	None	None	None
AREA OF APPLICATION	Internal/ External	Internal/ External	Removable Parts	Immersion of Removable Parts	External
QUANTITY OF WASTE PRODUCED	Moderate - Large	Moderate - Large	Small	Small	Small
WORKER EXPOSURE	Moderate	Moderate	Low	Low	Low
OVERALL COST	Moderate	Moderate-High	High	Low - Moderate	Low
COMMENTS	May not remove tightly adhering surface films	Removes tightly adhering contaminants.	Effectively cleans cloth, rubber, and plastic.	Very effective for cleaning small parts.	Removes weekly adhered, wet or dry contaminants

Ultrasonics

Ultrasonic cleaning applies to small parts that can be removed and placed in a tank filled with chemical solvents, liquids with abrasives, or detergents. The maximum standard tank size commercially available is about 1.5m X .75m X 1m deep, but larger sizes can be special ordered (11). Cleaning action results from the conversion of electrical energy to high frequency sound waves which create billions of tiny bubbles in the cleansing solution. Forming and collapsing these bubbles produce scrubbing action that penetrates recesses and goes around corners of immersed parts.

The chemical and physical properties of the cleaning liquid are quite important in determining its effectiveness. Factors such as vapor pressure, surface tension, viscosity, and chemical activity are important (11). All of these are affected by temperature; in general, the cleaning ability increases with temperature up to a point. Typically, the formation and collapse of bubbles reach a maximum at about 15°C below the normal boiling point of the liquid (11).

Undissolved solids can adversely affect cleaning by deflecting or reducing the ultrasonic energy; therefore, the liquid should be filtered. Reintroducing the filtered liquid back into the tank should be done with minimal turbulence because it will interfere with wave transmission and reduce cleaning effectiveness. Small objects can be cleaned in a basket (preferably made of metal since it doesn't absorb ultrasonic energy) immersed in the liquid. Items should be rinsed after removal from the ultrasonic cleaning tank.

Ultrasonic cleaning equipment is well developed and has proven effective in industrial use for removing grease and other forms of dirt. Initial equipment costs would be comparable to most other methods, but the size of the unit purchased would be the determining factor. The cost of a two-gallon bench-top unit in a 1981 Labmart catalogue was $540 per unit. Labor disposal costs would be low, and because the liquids are confined, redistribution of contaminants would be minimal.

Vacuum Cleaners

A vacuum cleaner for hazardous contamination cleanup consists of a flexible hose for collection, a canister to support the ultrafiltration system and contain accumulated waste, and a motor to provide negative pressure to operate the system (37). Both wet and dry vacuum systems are available and would be useful to clean the mobile response unit of dust and dirt before and after the pressure washing.

The design of industrial vacuum cleaners, sizes, and configurations, vary widely. Filtration systems also vary in terms of their efficiency and capability for dry and wet pickup. A filter designed specifically for recovery of toxic and nuisance dusts is called a High Efficiency Particulate Air (HEPA) filter; it is 99.97 percent effective to 0.008 mm. Activated carbon filters capable of eliminating vapors from vacuum exhaust are also commercially

available. Los Alamos Scientific Laboratory has used a specially designed vacuum cleaning unit equipped with disposable HEPA and activated charcoal filters to remove spills of aromatic amine cancer suspect agents (16).

Table 7 presents the names, addresses, and phone numbers of several vendors who supply portable industrial vacuum cleaners. Nilfisk model GS83 with accessories costs $2,652. Another vendor, BVC Beamco, Inc., supplies industrial vacuum units costing $1,985-$2,280.

TABLE 7. VACUUM VENDORS

1. Hako Minuteman
   111 South Route 53
   Addison, Illinois 60101
   (312) 627-6900

2. BVC Beamco, Inc.
   280 Polaris Avenue
   Mountain View, CA 94043
   (415) 967-6268

3. Nilfisk of America, Inc.
   224 Great Valley Parkway
   Malvern, PA 19355
   (215) 647-6420

Summary of Physical Decontamination Techniques

The more promising methods, because of their practicality and cost-effectiveness, include:

- Ultra-high-pressure water at 1,000 atm
- Mechanical methods using brushes
- Wet abrasive techniques.

These methods should be used in conjunction with contamination avoidance techniques, such as protective coatings. Whether the coating is permanent or temporary influences the required severity of the cleaning action. Variability in water pressures used in ultra-high-pressure cleaning makes this technique adaptable to a variety of surfaces. Wet abrasives can be carefully controlled

so they do not severely abrade surfaces; they help control the release of contaminant dust, which is a severe problem with dry abrasives. Variations in bristle hardness and scrubbing time make brushes very adaptable.

Vacuum cleaners may be useful for removing gross particulate contamination so subsequent steps in the decontamination process can be more effective. Vacuums may also be effective in cleaning up residual airborne-deposited grit remaining after abrasive use.

SECTION 6

CASE STUDIES: DECONTAMINATION OF SURFACES

INTRODUCTION

Published studies describing past experiences with chemical decontamination were reviewed to identify techniques with potential applicability to mobile response units at hazardous waste sites. Three case studies were developed. They describe:

- Decontamination of the Binghamton State Office Building
- Decontamination of the Incinerator Ship M/T Vulcanus
- Decontamination of the Three Mile Island Nuclear Reactor No. 2.

Each case study and the relevance of its data is discussed in this section.

DECONTAMINATION OF THE BINGHAMTON STATE OFFICE BUILDING

On February 5, 1981, a New York State Office Building in Binghamton, New York, experienced a fire which resulted in the contamination of virtually all internal building surface areas with PCBs, dibenzodioxins, and dibenzofurans. Cleanup activities have focused on the removal of highly toxic 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)(38).

Two methods of surface decontamination using solvent rinses were used successfully in the Binghamton Office Building. Surfaces readily accessible to workers were hand-scrubbed using Triton X-100 cleaning solution. Inaccessible areas like air ducts were decontaminated by scrubbing with a BMS Cat cleaning solution. Both Triton X-100 and BMS Cat cleaning solution are are proprietary formulations containing nonionic detergents. Triton X-100 is manufactured by Rohm and Haas in Philadelphia, Pennsylvania, and BMS Cat solution, by BMX of Fort Worth, Texas. These solutions were selected because of their known low toxicity and ability to remove TCDD (Bob Westin, Versar Inc., personal communication, 1984).

After vacuuming to remove loose soot and particulate matter, Triton X-100 was spread on the decontaminated surface, hand-scrubbed, and rinsed with water. The New York Office of General Services personnel reported that the

X-100 produced acceptable results on nonporous materials such as glass, metal, and plastic; it has proven unsatisfactory for use with quarry and ceramic tile (presumably due to the tile's porosity) (Dave Rings, New York State Office of General Services, personal communication 1984). Versar, Inc., which is managing the cleanup activities under contract to New York State, reported that many solvents and detergent formulations were also successful in cleaning the tiles (Westin, 1984).

Inaccessible air ducts in the building were cleaned by spraying a coating of BMS Cat, scrubbing the surfaces using sponges on poles, and rinsing with water. Duct work was then coated with Thoroseal to seal in any contamination which may have been missed (39).

Versar reports that the cleaning reduced surface contamination to a level of approximately 3 nanograms per square meter or less (Westin, 1984). As of this writing (June 1985), the New York State Department of Health (DOH) has not determined an acceptable level of surface contamination (John Hawley, New York State Department of Health, personal communication, 1984). However, the 3 nanograms level detected in the Binghamton facility is well within the contamination levels, ranging from 3.3 to 28 nanograms per meter, now under consideration by DOH (Hawley, 1984).

Since these clean up activities generated large volumes of water, a water treatment system was built in the basement of the building to filter or rinse water before discharging it to the city's sanitary sewer system. This treatment system filtered contaminated particles by a series of high rate sand and activated charcoal filters. Large capacity (50,000 liters) and two medium capacity (19,000 liters) plastic tanks were needed for this treatment system (39).

Several measures were taken to insure the safety of cleanup personnel decontaminating the Binghamton Office Building. A trailer containing security offices, showers, rest rooms, and lockers positioned at the loading dock provided the only entry/exit to the building. Before leaving the premises, all personnel were required to remove protective clothing and to shower thoroughly, using the showers provided.

Personnel were required to wear Level C protective clothing including: socks, sneakers, and rubbers; underwear, coveralls, and outer Tyvek protective suits; and cotton and rubber gloves. It was also mandatory for all personnel to wear full face respirators featuring activated carbon and high efficiency particulate filters. After each use, the respirator filters, Tyvek suits, and hand gloves were discarded. In addition, an Air Pollution Control System was used to ensure a constant flow of clean outdoor air through the building (39). Vented air was filtered through the Air Pollution Control System on the roof before being released outdoors.

Workspace air within the Binghamton Office Building was sampled and tested before and during rehabilitation of the facility. Before work began, ambient air samples were gathered from the normal operating areas of the heating, venting, and air conditioning systems. Throughout the decontamination

process, air moving through the Air Pollution Control System was tested periodically. In addition, monthly industrial hygiene samples were taken to test for PCB levels. As of the date reported, PCB levels well below the established acceptable level of 0.2 to 0.3 micrograms per cubic meter were detected (39).

MOTOR TANKER (M/T) VULCANUS DECONTAMINATION

In July and August 1977, U.S. Air Force stocks of Agent Orange were incinerated on the Motor Tanker (M/T) Vulcanus while operating in the Pacific Ocean. Shipboard surfaces contaminated with 2,3,7,8-TCDD (present in Agent Orange in an average concentration of 1.9 ppm) were successfully decontaminated using separate saltwater and acetone rinses.

Surface contamination of various metal parts of the Vulcanus occurred once when the incinerator plume impinged on the ship and several times when small amounts of Agent Orange spilled from the holding tanks. Suspected areas were tested for contamination by taking wipe test samples. If any surface contamination was detected, the area was washed with a high-pressure saltwater spray. Small contamination areas were handscrubbed with acetone-laden rags and rinsed with water. In every instance, subsequent wipe tests were taken and revealed no detectable herbicide residues. Data describing the quantities of remaining surface contamination were not available (40).

The Vulcanus storage tanks were decontaminated at the end of each operation by serial rinsings of herbicide free of, or containing less than, the 0.02 ppm detectable limit of TCDD. After being completely drained of waste herbicide, each tank was filled with TCDD free herbicide to dilute the TCDD content of waste herbicide residuals. The TCDD free herbicide rinse was transferred from tank to tank until all tanks had been serially drained and rinsed. As a result, tank TCDD residual contamination levels were reduced to below 50 miligrams per square meter. All rinsewaters were incinerated for final disposal (40).

The air, water, and surface areas used by or exposed to crew members were regularly tested for TCDD contamination. Wipe samples of the M/T Vulcanus surface areas were taken by rubbing an area approximating one square meter with Whatman 41® filter paper discs. Sample discs were soaked in five milliliters of benzene for one half hour before the resultant extracts were analyzed on board by gas chromatography. Work space air samples were taken at various places with ten milliliter gas sampling syringes and four stationary work space air monitors positioned in high traffic areas. The stationary monitors consisted of a single 3 mm ID glass tube filled with 25 mm of Chromosorb 102® attached to an air pump. These tubes were changed daily. Potable water samples, taken after each operation, and the work space air samples were delivered to a nearby laboratory (Johnston Island Battelle Columbus Laboratories) to be analyzed by gas chromotography using electron capture detection (40).

Personnel working on the M/T Vulcanus were protected from TCDD contamination in several ways. Areas containing Herbicide Orange were defined and distinct boundries drawn between contaminated work areas and clean living areas. After each shift, the protective clothing was discarded in disposal cans, which were incinerated daily. A shower installed directly inside the

contaminated work area was used by personnel leaving the contaminated areas. In addition to these precautions, the air, surface, and drinking water were regularly monitored for TCDD contamination (40).

THREE MILE ISLAND DECONTAMINATION

Electropolishing techniques used to decontaminate radioactive metal parts at the Three Mile Island (TMI) nuclear reactor have potential application in decontaminating mobile incinerators at hazardous waste sites. Electropolishing is an electrochemical process that produces a smooth, polished surface on a variety of metals and alloys. Studies have shown it to be a rapid and effective decontamination technique for metallic surfaces. Electropolishing has been used to successfully decontaminate compositions ranging from steel, copper, and aluminum, to stainless steel and highly alloyed, corrosion and heat-resistant materials. Electropolishing has been found effective for contamination that is baked-on, ground-in, or otherwise difficult to remove using conventional decontamination procedures.

Although electropolishing solutions are generally based on phosphoric acid, an electrolyte based on sodium nitrate has been developed for the electrocleaning of highly radioactive surfaces at TMI. This electrolyte causes the contamination and the removed dissolved metals to form a precipitate that easily separates from the liquid. No data were available describing the effectiveness of electropolishing in removing nonradioactive surface contamination. However, the fact that 0.05 mm. of the metal surface or more can be removed by electropolishing indicates that it removes chemical surface contamination effectively. It should be noted that electropolishing is only effective for decontaminating bare metal and not painted surfaces (41).

Another advantage of the electropolishing technique is that it may be used to decontaminate remote, complex, or otherwise inaccessible surfaces. At TMI, several systems are being developed for using the electropolishing technique on different surface types. These devices will enable electropolishing of large flat walls, pipe interiors, loose metal items, tools, and fittings. For example, large planar surfaces will be electropolished by a mobile device which places an electrolyte pool with a parallel cathode against a flat contaminated surface. Rough, uneven metal surfaces may be electropolished by pumping a stream of electrolyte fluid over the surface through a cathode lined gun-nozzle. A device is also under design to preclean and scrub rough surfaces with a porous insulator "sponge" and electrolyte fluid. Loose contaminated metal items may be electroplated in a tank lined with cathodes and filled with electrolyte fluid (41).

An electropolishing technique for decontaminating internal pipe surfaces has also been developed and successfully tested by United Nuclear Industries Inc. This device consists of a 60 cm. long tubular cathode placed inside an electrolyte filled pipe. Each 60 cm. section of pipe is electropolished for 20 minutes at a current approximating 1076 amps/m^2 before being rinsed with water. At the conclusion of these electropolishing treatment tests, the measured contamination was reduced by about 4 R/hr in low radiation areas and by more than 40 R/hr in areas more contaminated with radiation. This electropolishing technique, in addition to those previously mentioned, may provide a versatile means of decontaminating a variety of difficult surfaces (41).

CASE STUDY CONCLUSIONS

Of these three case studies, only the Binghamton Office Building cleanup offers tangible results regarding the efficiency of decontamination techniques for removing dioxin and related compounds. However, the personnel protection programs and other decontamination methods used and under development for these cases do provide practical examples for future applications. From the cases studied, the following conclusions may be drawn:

- Specific nonionic cleaning solutions provide an acceptable means for decontamination.
- Electropolishing techniques may provide useful methods for chemical decontamination in the future.
- Several practical methods for ensuring personnel protection include: 1) isolation or distinction of contaminated areas 2) use of disposable cover suits and gloves 3) installation of showers at exit points from contaminated area.

Specific evidence on the effectiveness of decontamination was only available for the Binghamton Office Building Project. Although the M/T Vulcanus Technical Report stated that high pressure saltwater rinses and acetone washings were effective in reducing TCDD contamination, specific data on test results were lacking. Therefore, unless actual data become available, defendable conclusions on the effectiveness of this method may not be made.

Test results reported from decontamination of the Binghamton Office Building do prove that dioxin levels of approximately three micrograms per square meter are achievable using specific nonionic detergents. Since this level of 3 micrograms/square meter is well below the units now being considered acceptable by the New York State Department of Health, we conclude that the nonionic detergents used, BMS Cat and Triton X-100, are capable of effectively removing surface dioxin contamination.

Although unproven, the electropolishing techniques employed at Three Mile Island may be adaptable to chemical decontamination. Chemical contaminants are likely to be removed during electropolishing; however, unless the contaminants are precipitated with the removed surface metal or otherwise fixed or degraded, the possibility exists of recontaminating the surface during contact with the contaminated electrolyte.

Several procedures were successfully implemented to insure the safety of personnel working at the Binghamton Building and aboard the M/T Vulcanus. In both cases contaminated areas were isolated by specifically defined borders. Tight security for all personnel entering and exiting the contaminated areas of the Binghamton Building was easily achieved by sealing all but one access point to the building.

Although the borders between the contaminated and uncontaminated areas aboard the M/T Vulcanus were more difficult to define and monitor, this system worked effectively on board ship. Personnel Safety plans for both projects also required that protective clothing including disposable coverall suits and boots be worn in contaminated areas. Cellulose coveralls used aboard the M/T Vulcanus were described as effective, comfortable, and inexpensive (40).

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APPENDIX A

FACTORS FOR UNIT CONVERSION

MASS

1 kg = 1000g = 2.204621b = 25.27292oz

LENGTH

1m = 100cm = 1000mm = 39.37in

VOLUME

$1m^3$ = 1000 liters = 10^6ml = 35.3145ft^3 = 264.17 gallons

PRESSURE

1 atm = 14.696 lb_f/in^2 (psi) = 29.921 in Hg @ 0°C